PHENIX measurements of the collision system dependence of heavy quarkonia production

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On behalf of the PHENIX Collaboration

Quark Matter 2015, Kobe
September 29, 2015

New data from PHENIX:

U+U J/ψ suppression from RHIC 2012 Run (arXiv:1509.05380)

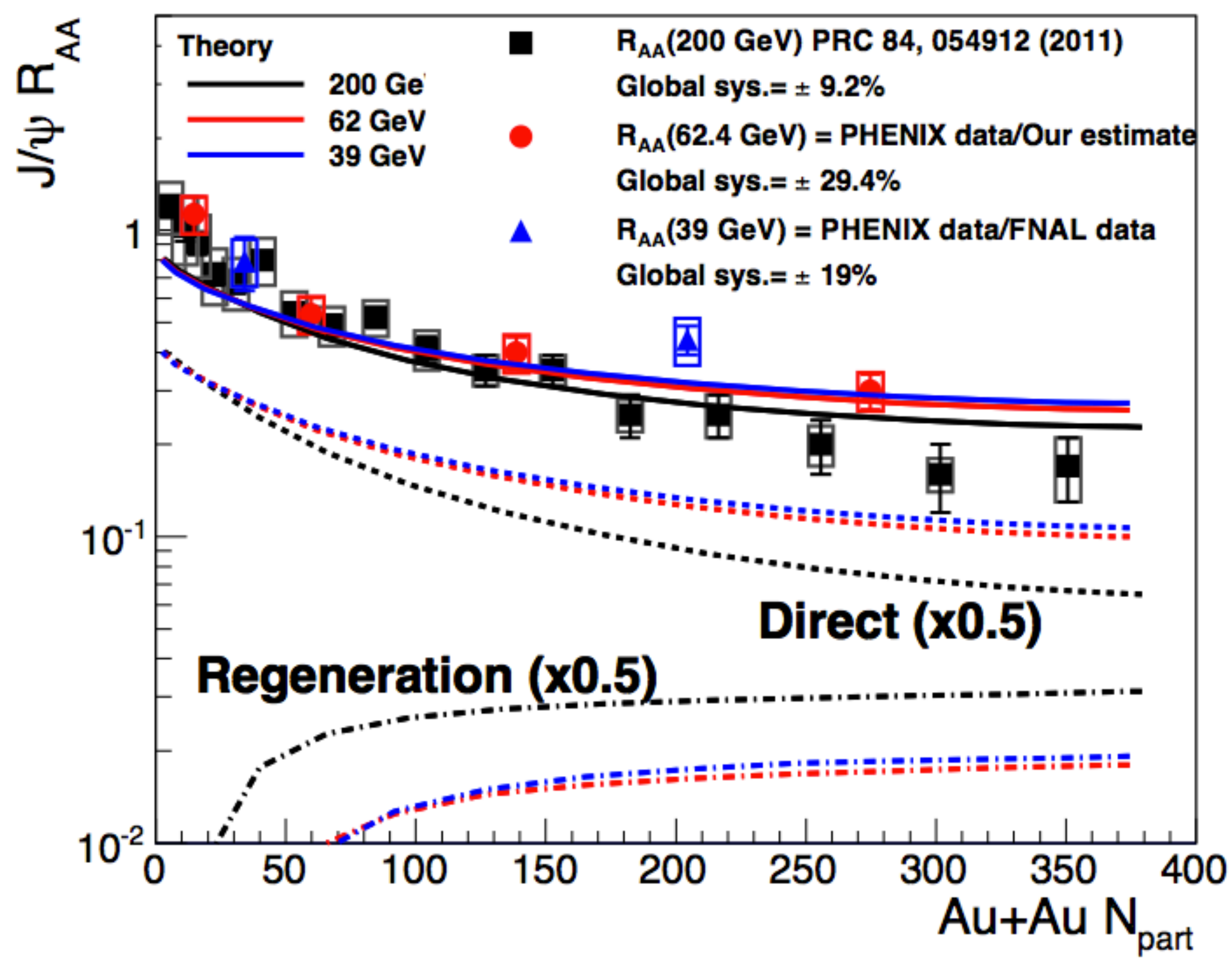
ψ(2S) / ψ(1S) ratios in p+p, p+Au, p+Al from 2015 Run

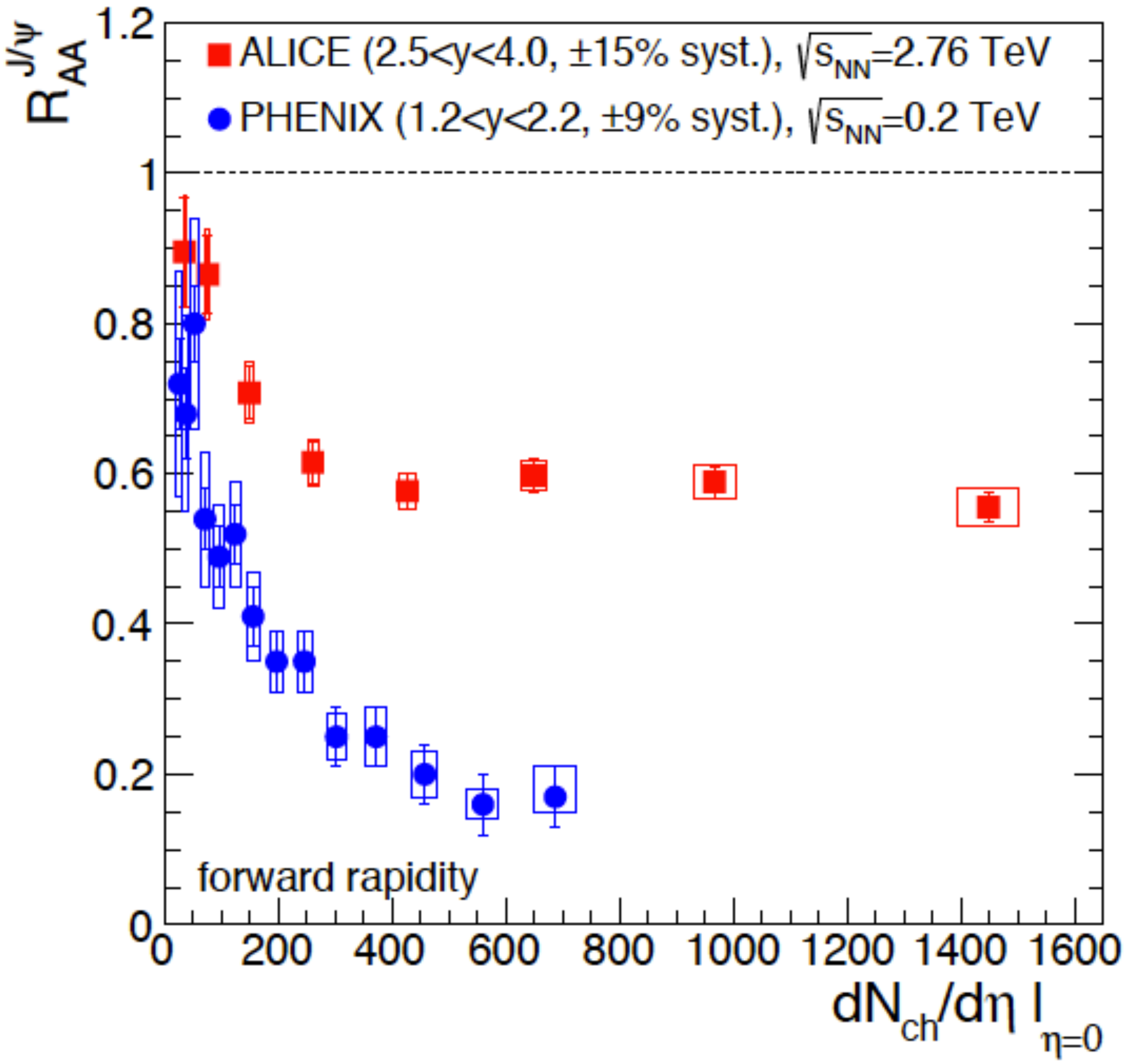
- Tracks measured with muon arms + FVTX detector
- Improved opening angle resolution separates J/ψ from ψ' in mass spectrum

LHC energy brings strong charm coalescence

J/ψ suppression much stronger at 200 GeV than 2.76 TeV for similar energy density - strong coalescence

At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression
- perhaps strongest at 200 GeV





In the model (PRC82, (2010) 064905) this similarity is due to a balance between color screening and coalescence

Where does coalescence start to dominate?

U+U collisions allow us to go to higher energy density at RHIC

Central U+U collisions should have:

- 15-20% higher energy density than Au+Au collisions
  - stronger color screening
- Increased charm production from ~ 25% larger N_{coll} values
  - stronger coalescence

J/ψ production in U+U collisions allows us to explore how the trade-off between color screening and coalescence evolves as we increase energy density and charm production

U+U measurements

In RHIC Run 12 we recorded 1.08 B minbias $\sqrt{s_{NN}}$ = 193 GeV U+U events

The p+p reference for R_{AA} is from the RHIC 2008 run

- Phys. Rev. Lett. 107, 142301 (2011)

The p+p cross section was reduced by 0.964

- Accounts for 200 → 193 GeV energy difference between p+p and U+U data
- derived from PYTHIA p+p simulations

Final J/ψ data from the muon arms ($1.2 < |y| < 2.2$) are now available

- arXiv:1509.05380

U deformation

Need N_{coll} to get R_{AA} for U+U. Requires a deformed Woods Saxon distribution of the nucleons in the U nucleus

$$\rho = \frac{\rho_0}{1 + exp([r - R']/a)}$$

where

$$R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

We considered two parameterizations of the deformation of the U nucleus:

Set 1 (Phys. Lett. B 679, 440 (2009)) - “conventional” description of the U deformation

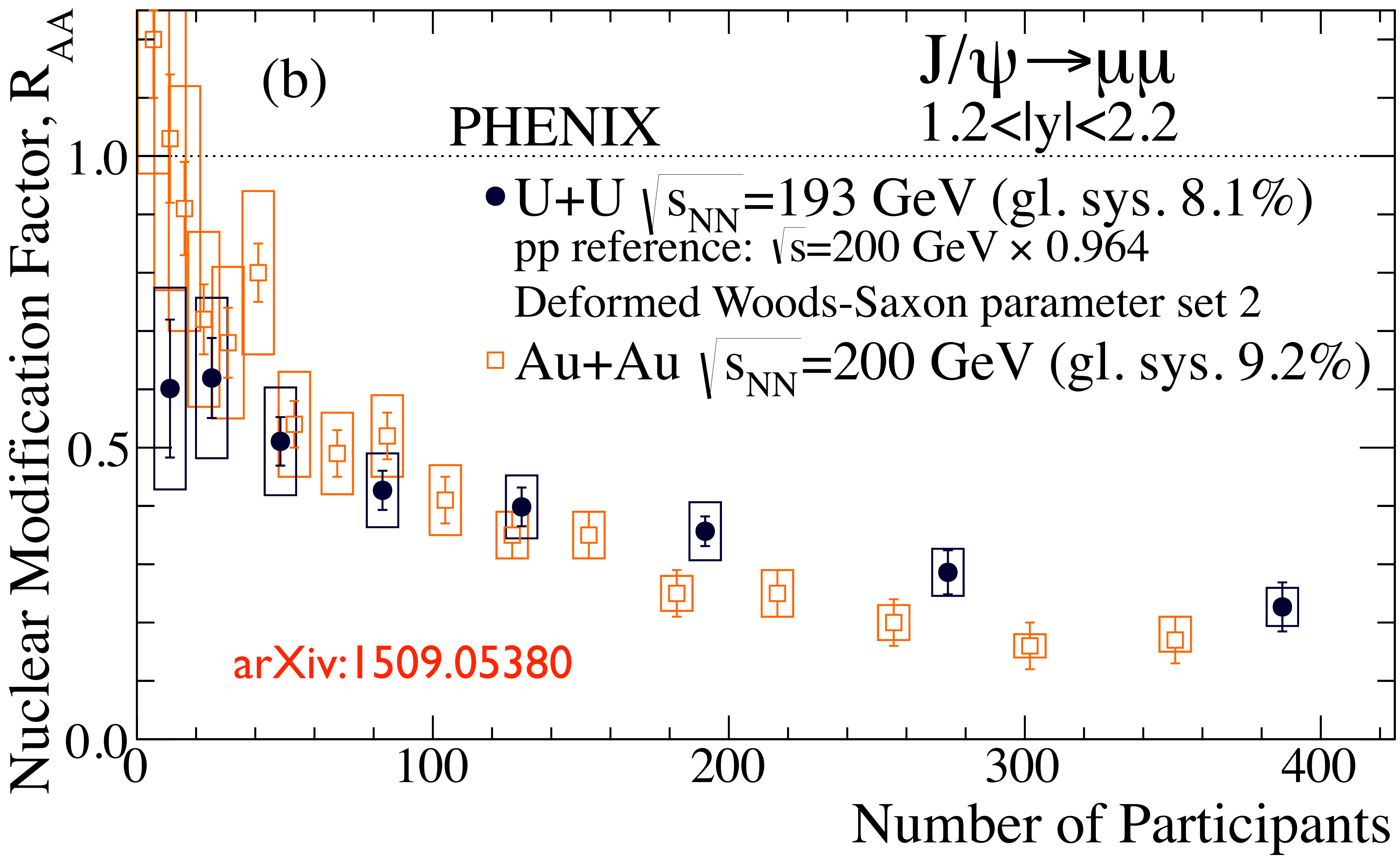
- The mean radius and diffuseness are taken from electron scattering

Set 2 (Phys. Lett. B 749, 215 (2015)) differs in 2 ways:

- Takes into account the finite radius of the nucleon
- Averages over all orientations of axis-of-symmetry
  - match average radius and diffuseness to values reported from electron scattering

The U+U R_{AA}

Start with the latest parameter set (2) to calculate R_{AA}



The U+U R_{AA} is noticeably larger than that for Au+Au

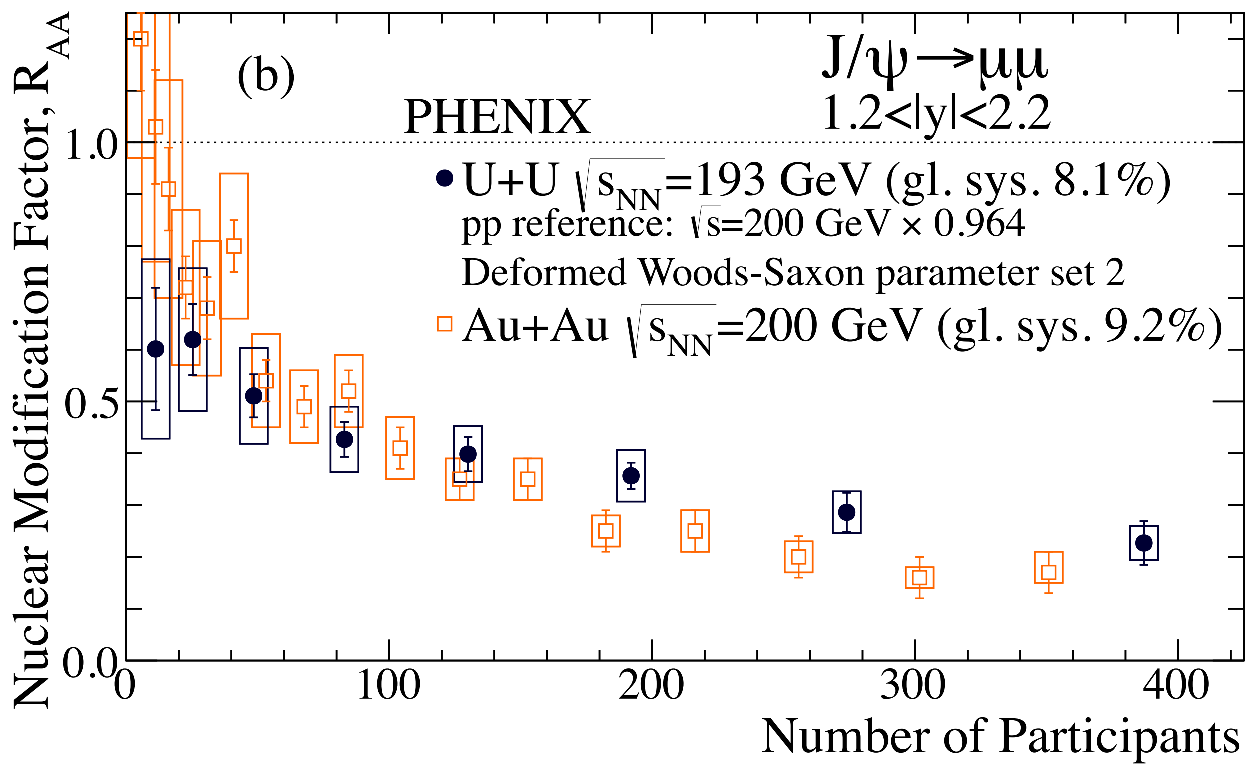
Effect of U deformation model

The parameters for set 1 are significantly different in their surface diffuseness:

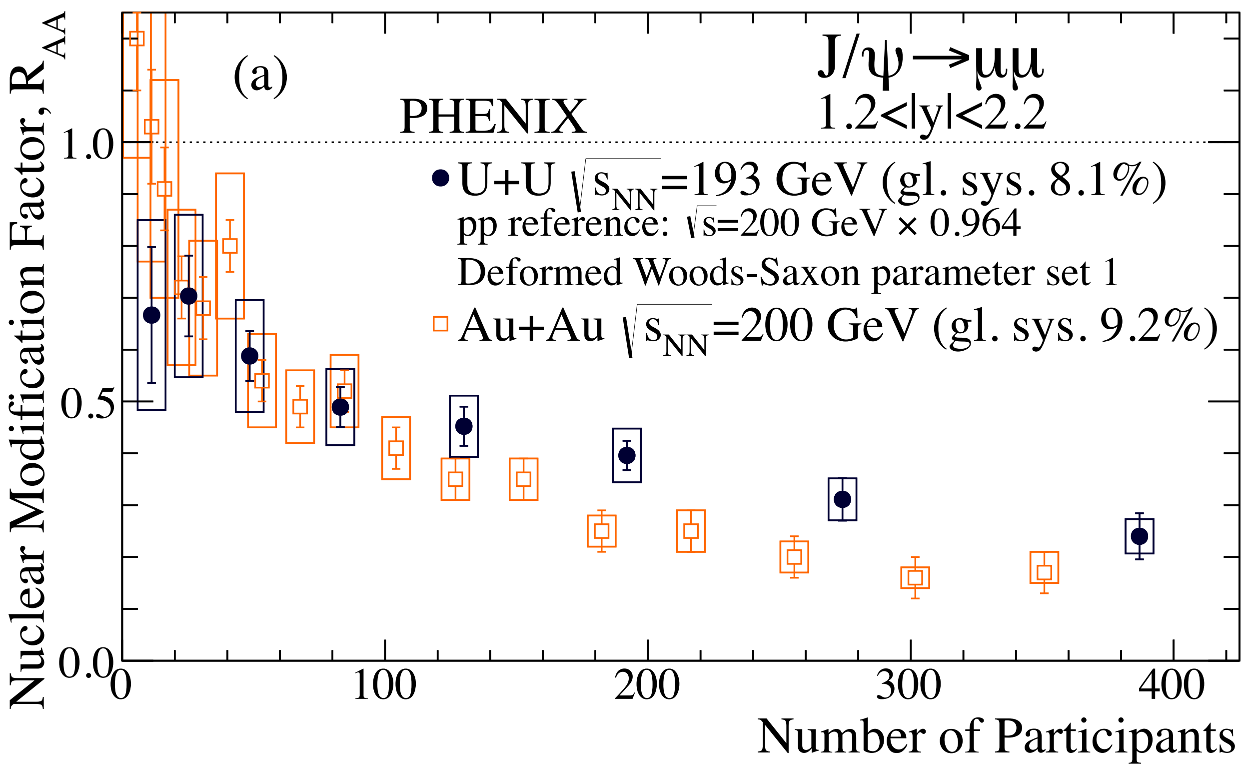
Parameter	set 1	set 2
$R\ (fm)$	6.81	6.86
$a\ (fm)$	0.6	0.42
β_2	0.28	0.265
β_4	0.093	0

Larger surface diffuseness for set 1 results in a less compact nucleus, a larger reaction cross section by 12%, and N_{coll} values that are smaller by 6 - 15%

Set 2



Set 1



Ratio of dN/dy for U+U and Au+Au

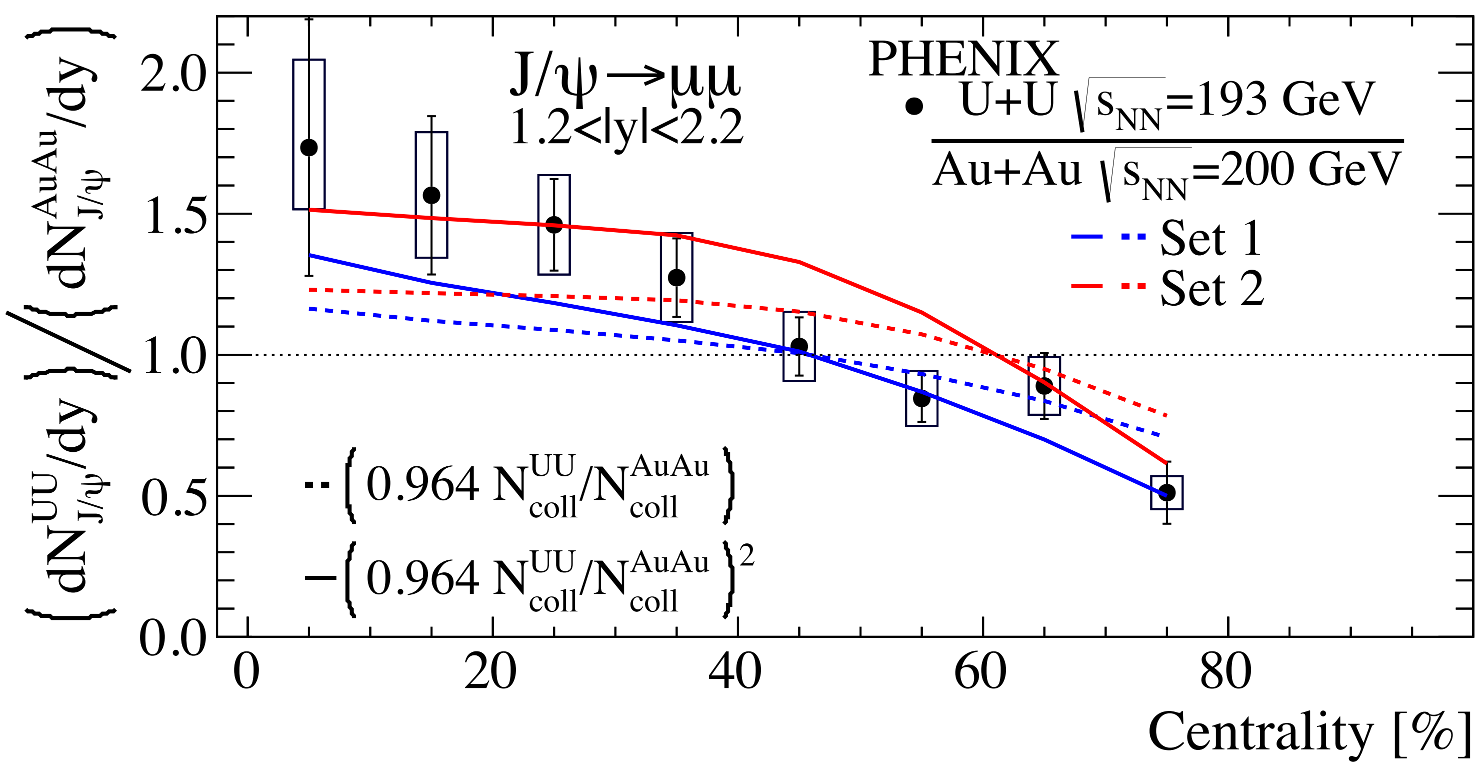
Make the experimental ratio of dN/dy values.

- Has the advantage that it does not rely on N_{coll}
- However our **expectation** for its behavior is determined by N_{coll}

Compare with curves showing how the ratio would depend on centrality if J/ψ production scaled with

- N_{coll} (dashed)
- N_{coll}^2 (solid)

arXiv:1509.05380



Curves shown for sets 1 and 2

For set 2, for central collisions the ratios tend to favor the N_{coll}^2 curve

For set 1, the ratios are consistent with both curves across centrality, slightly favoring N_{coll}^2 for most central collisions

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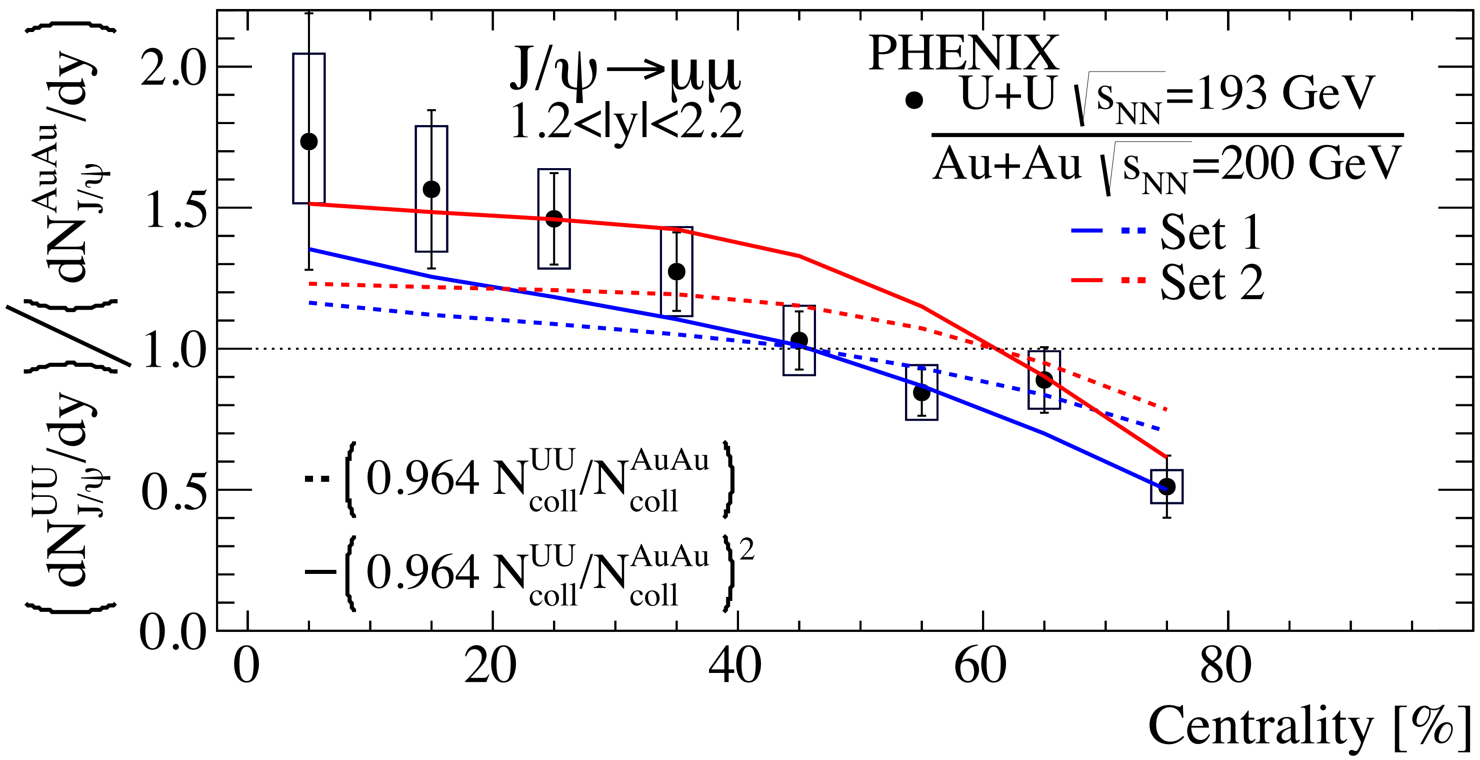

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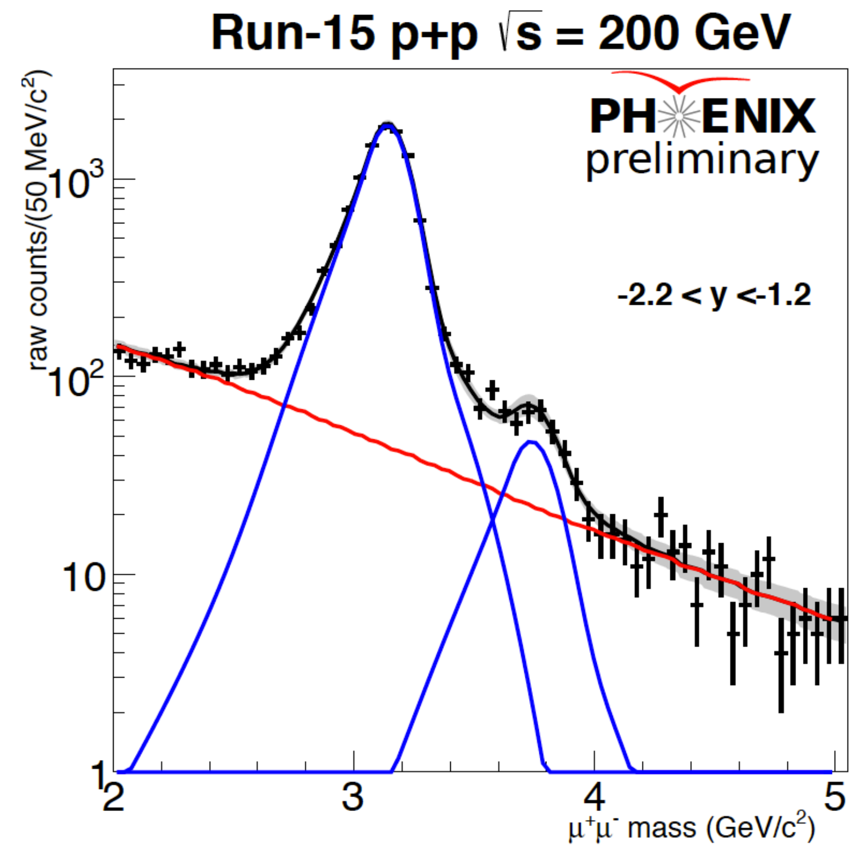
Consistent with a picture in which the increase in charm coalescence becomes more important than the increased color screening when going from Au+Au to U+U

Preliminary ψ' / J/ψ ratios in p+p, p+Al and p+Au

Preliminary ψ' / J/ψ ratios in p+p & p+Au

p+p, collisions

ψ' and J/ψ → $\mu^+\mu^-$ 1.2 < |y| < 2.2



Preliminary ψ’ / J/ψ ratios in p+p & p+Au

p+Au, collisions

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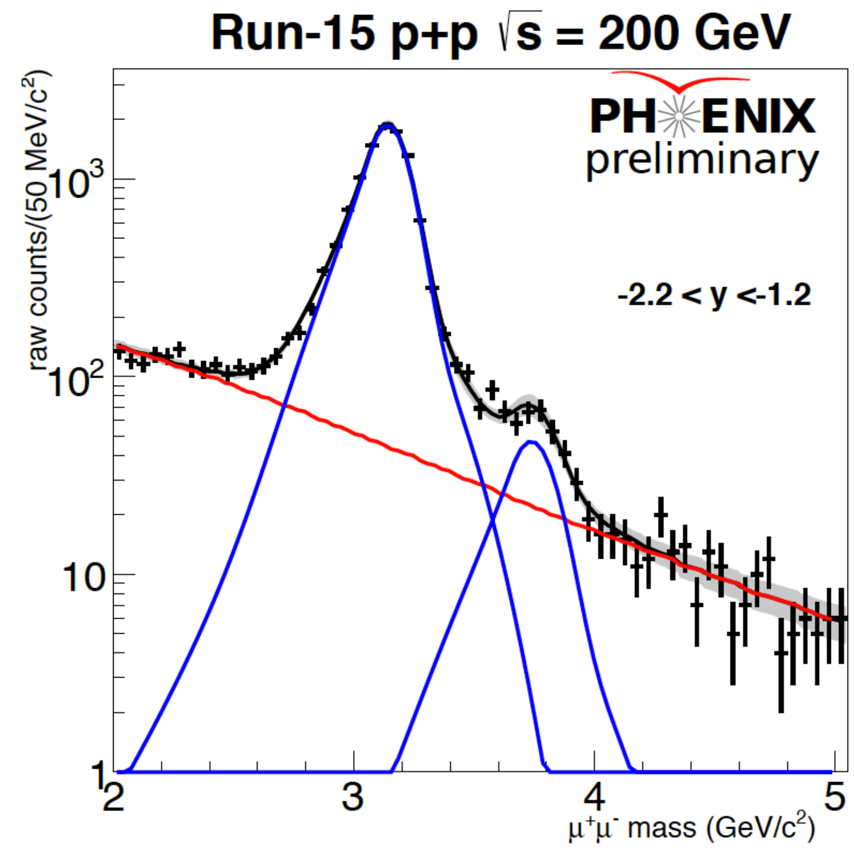
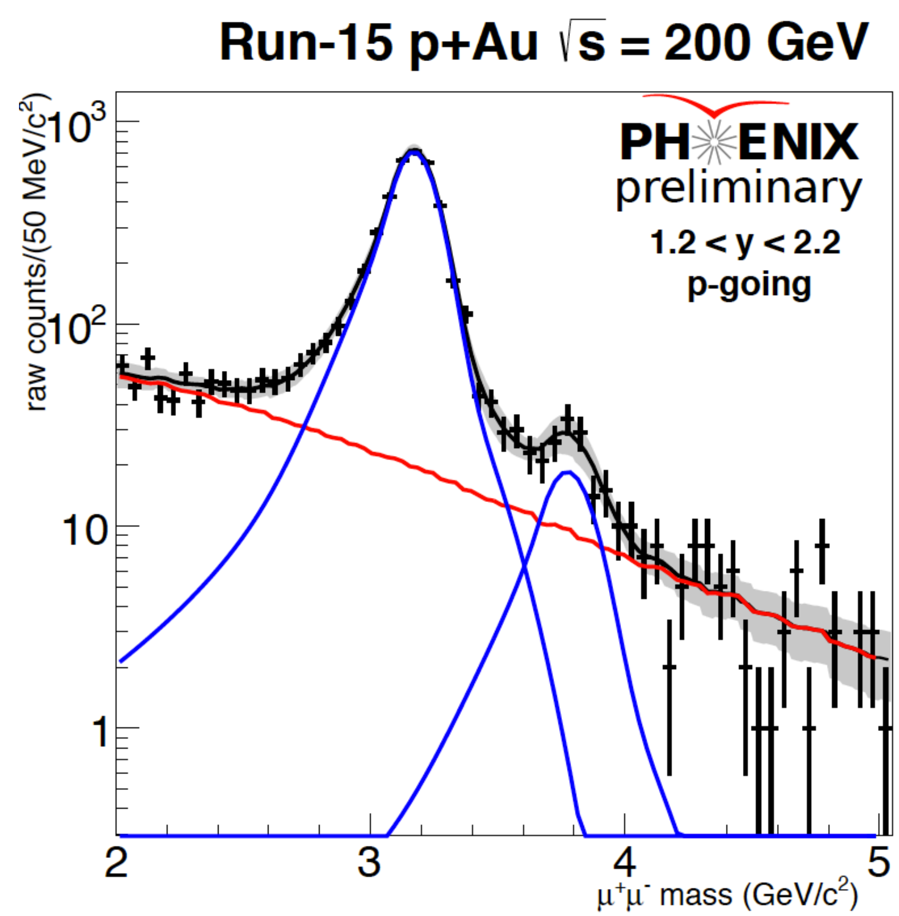
Fit method and cuts in p+Au identical to p+p analysis



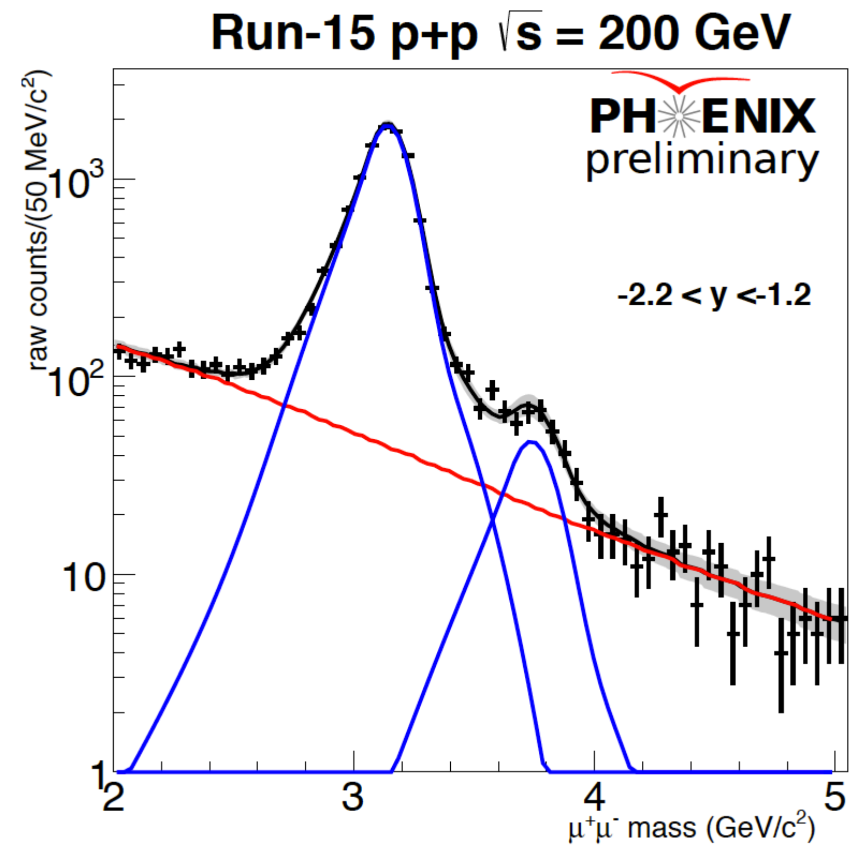


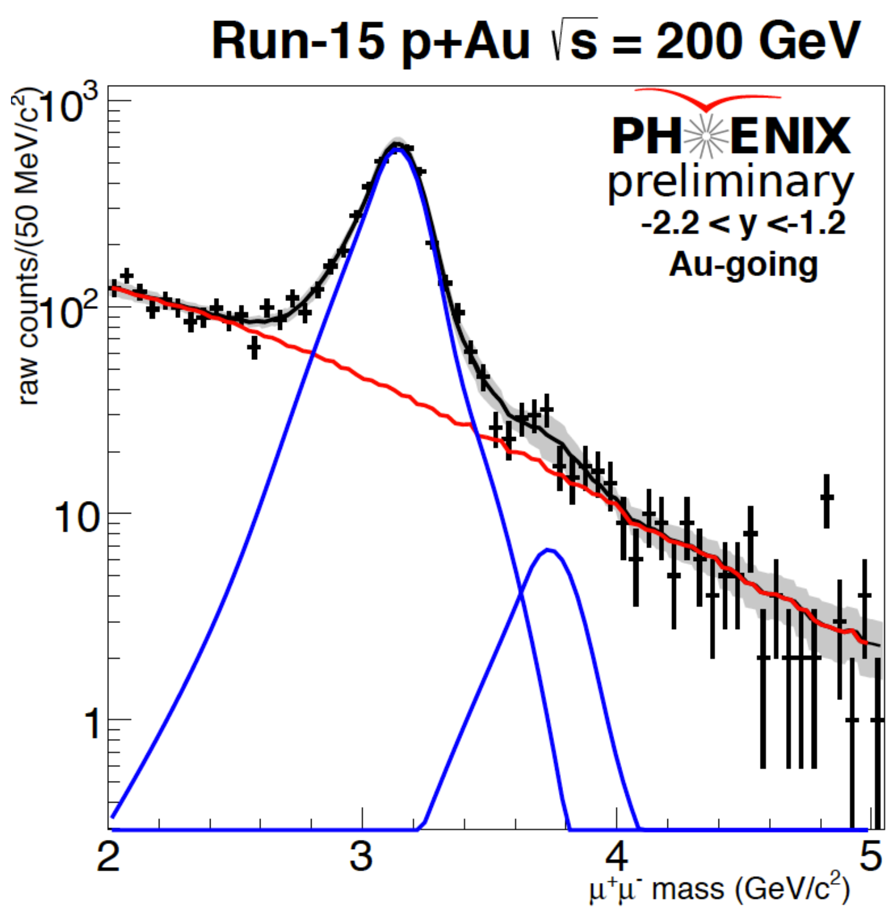
Preliminary ψ' / J/ψ ratios in p+p & p+Au

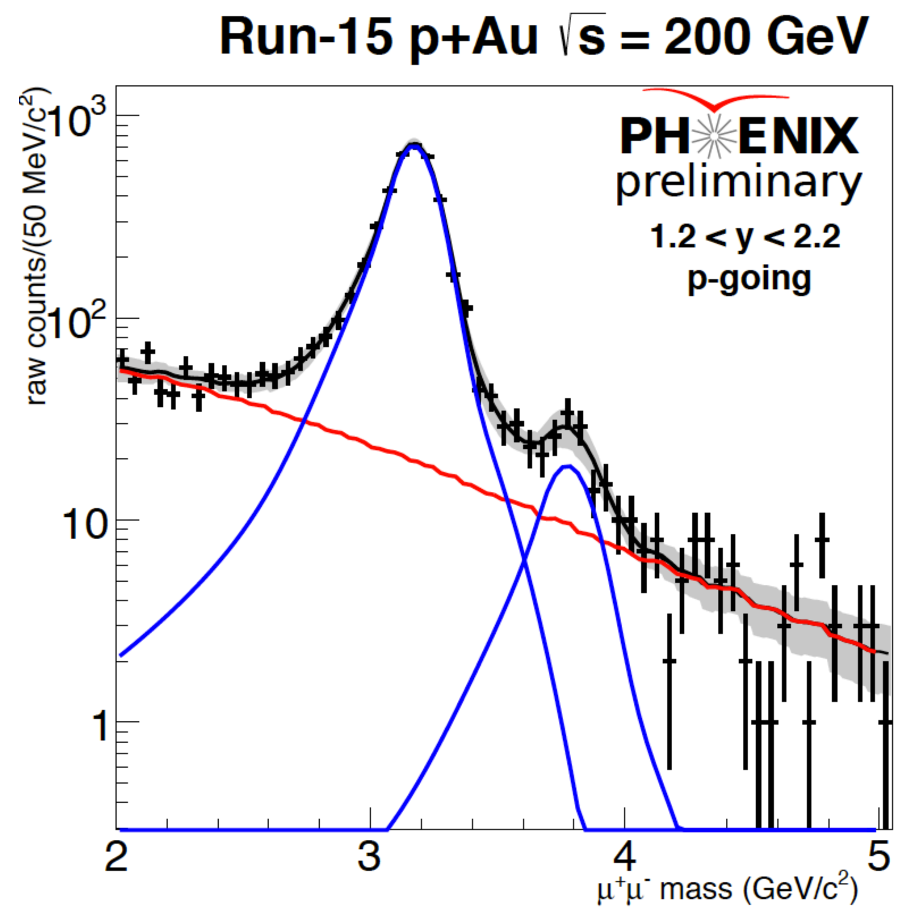
p+Au, collisions
ψ' and J/ψ → $\mu^+\mu^-$ $1.2 < |y| < 2.2$

Fit method and cuts in p+Au identical to p+p analysis

Stronger suppression evident in Au going direction





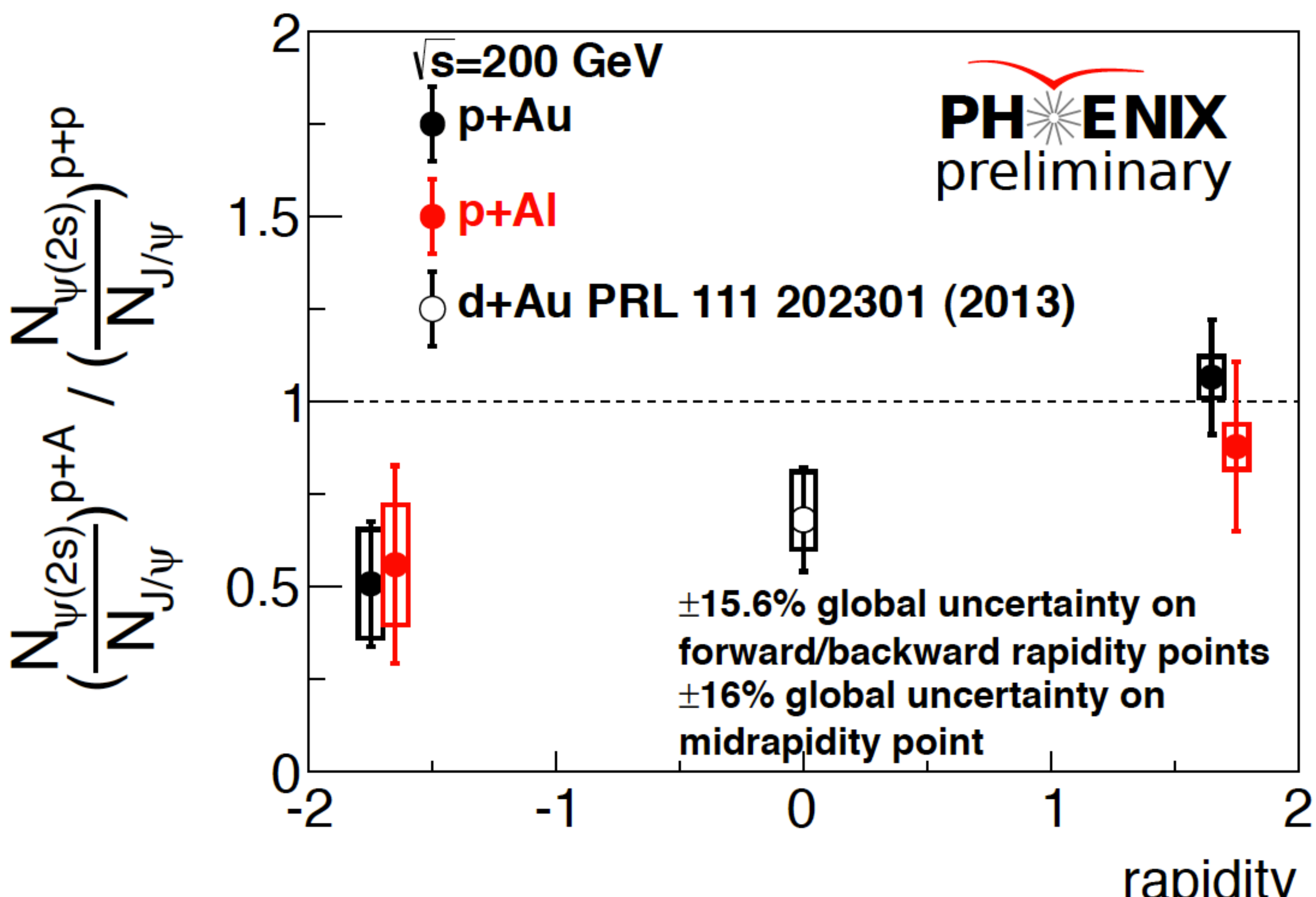


ψ’ / J/ψ ratios in p+Au and p+Al vs rapidity

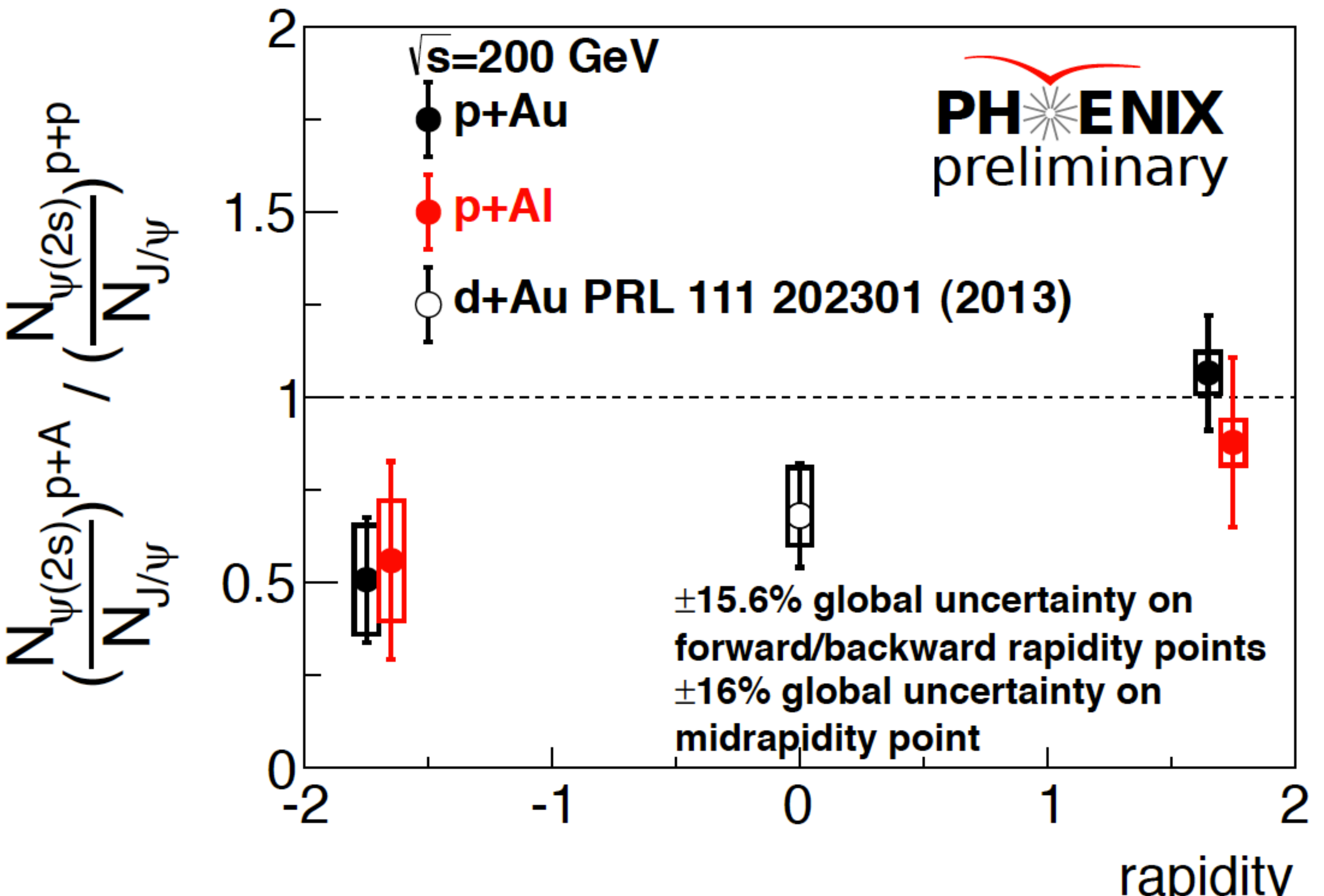
Centrality integrated ratio plotted vs rapidity for p+Au and p+Al

Midrapidity point is from d+Au

Strong suppression at backward rapidity, no suppression at forward rapidity



What causes the differential suppression?



0.1 - 0.3	0.02 - 0.05	0.004 - 0.01

nuclear crossing time τ (fm/c)

Can **breakup** in collisions with nucleons explain the differential suppression at y = -1.7?

No - the effect is much too small!

From PRC 87 (2013) 054910 - model of τ dependence fitted to world's data

Get ~ 1% - 7% effect in -1.2 < y < -2.2

What causes the differential suppression?

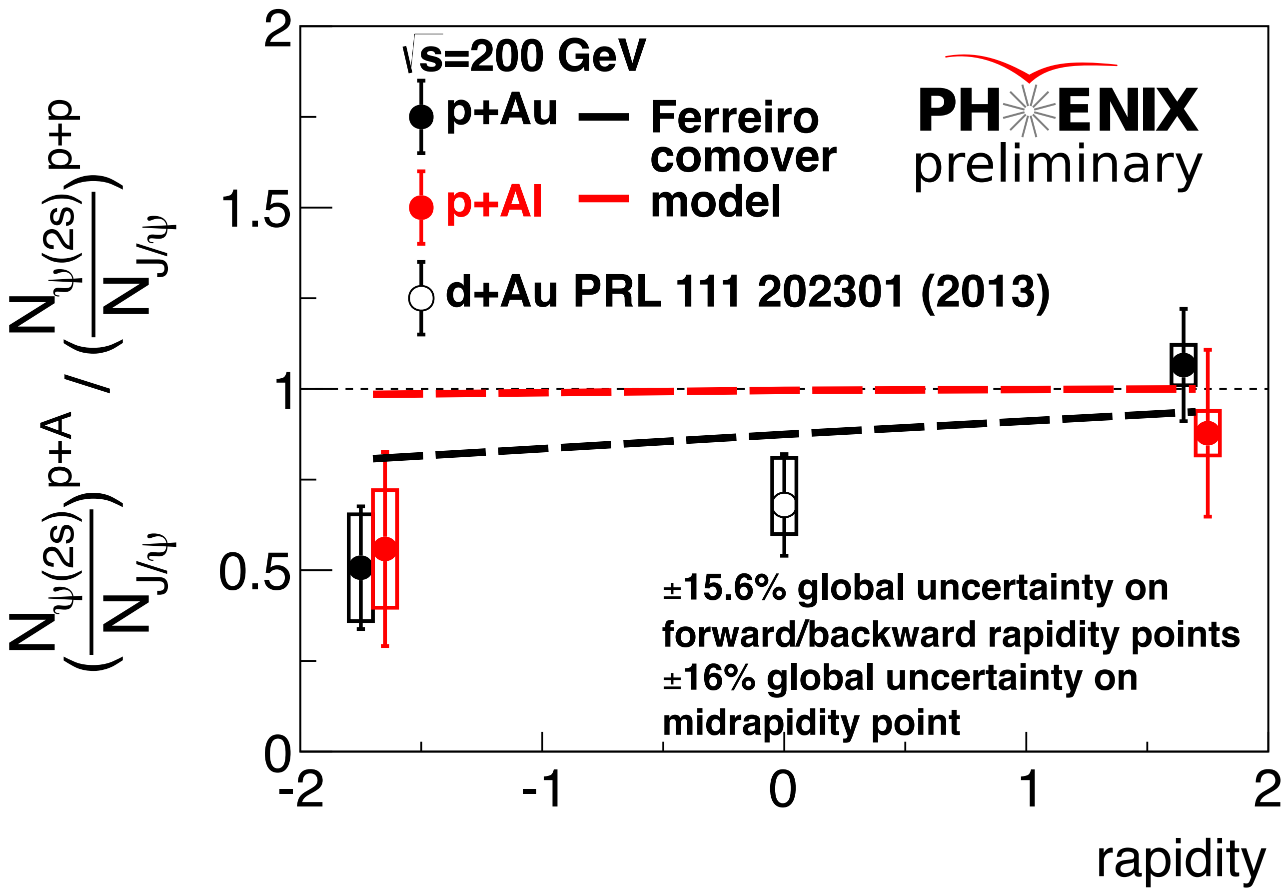
Since we have eliminated breakup, there is no CNM mechanism that could explain the strong suppression at backward rapidity

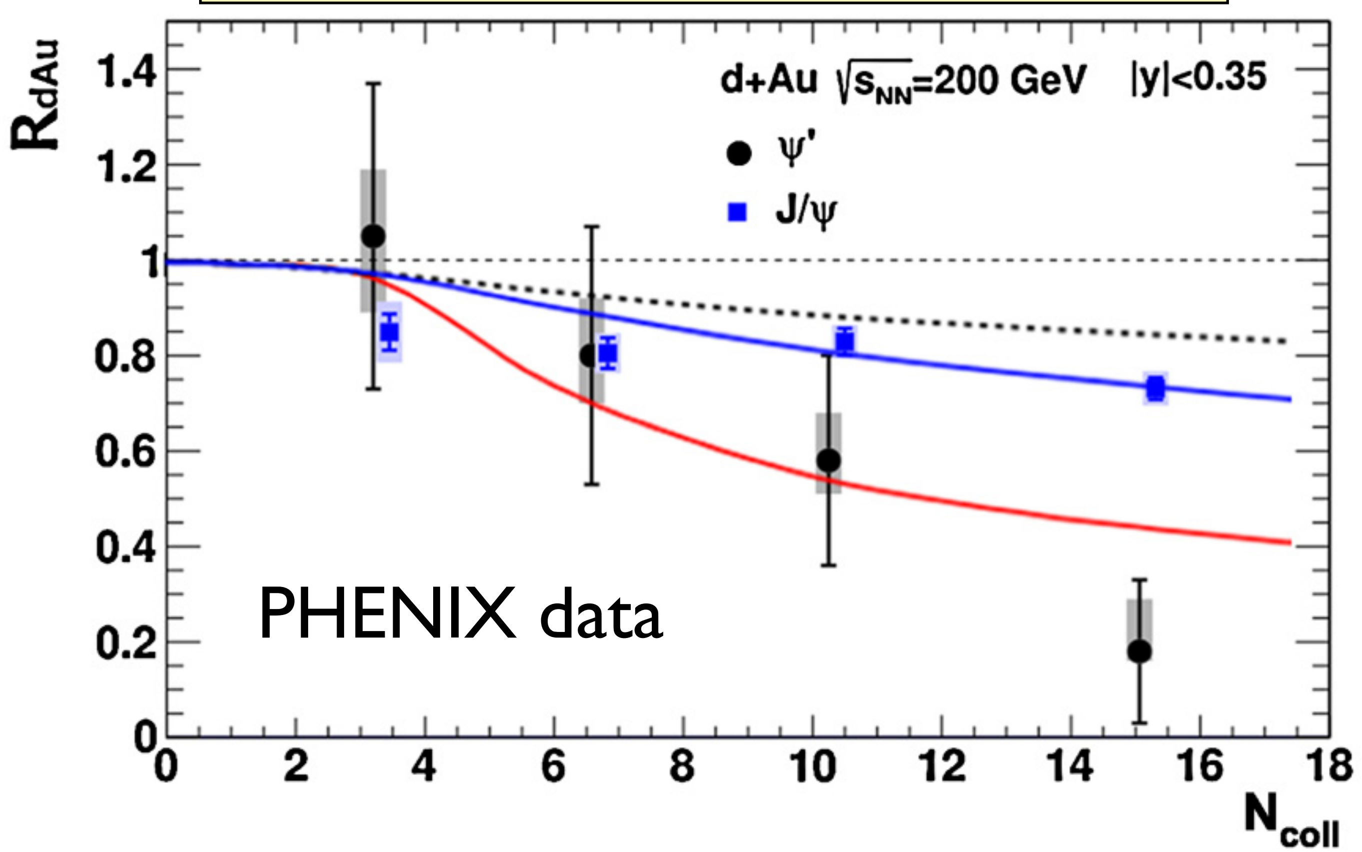
- That leaves final state effects

Final state effects:

- Suppression is caused by interactions with produced particles
- So it can occur after the charmonium leaves the target
- i.e. when the meson is fully formed

Ferreiro (PLB 749 (2015) 98)
"Comovers" in final state





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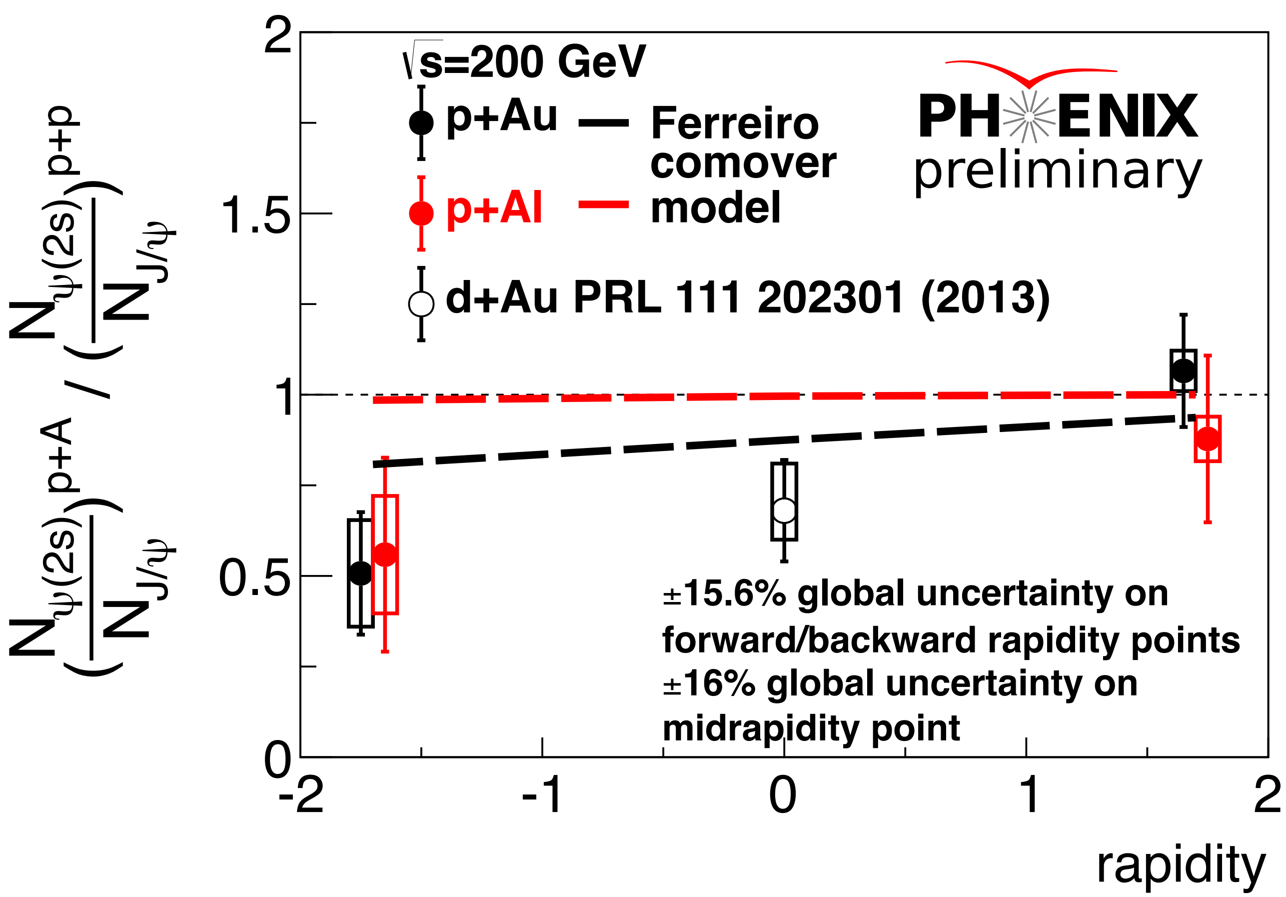
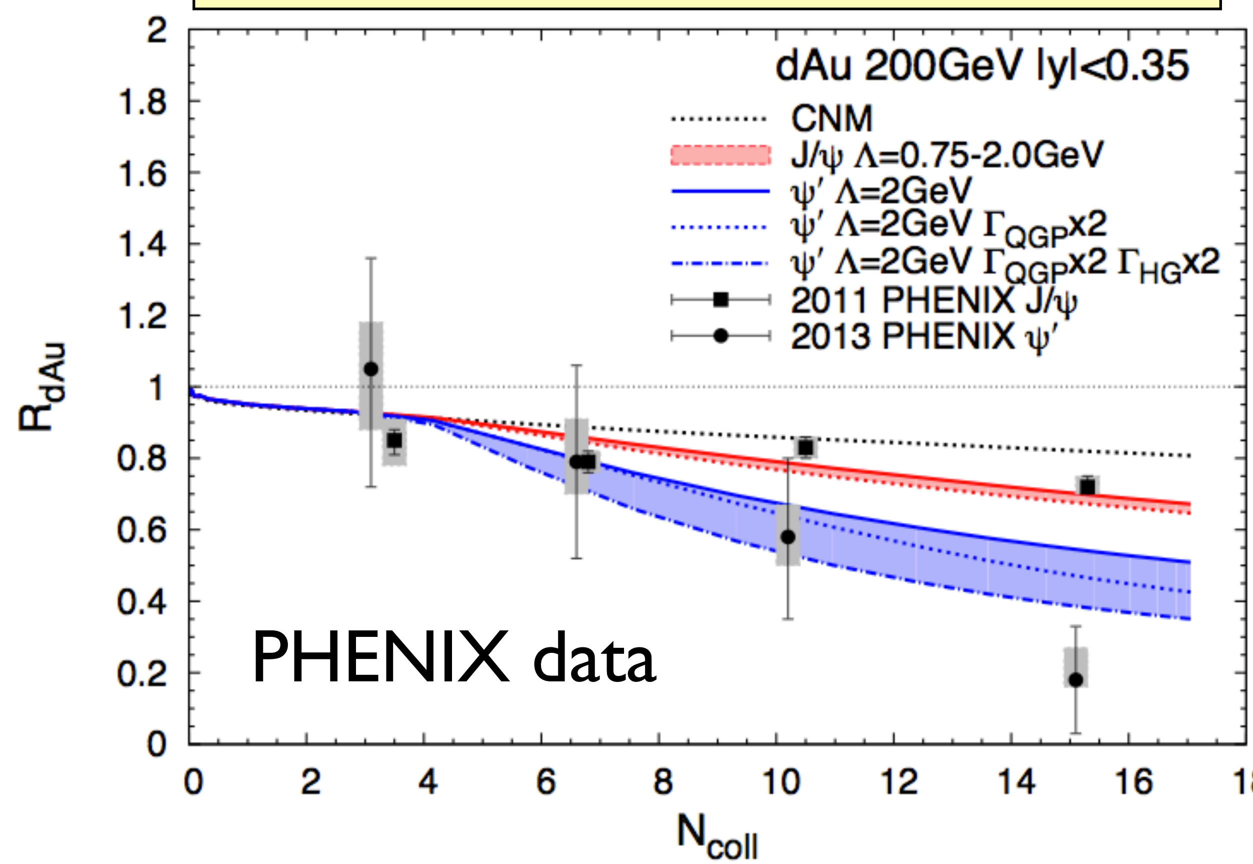


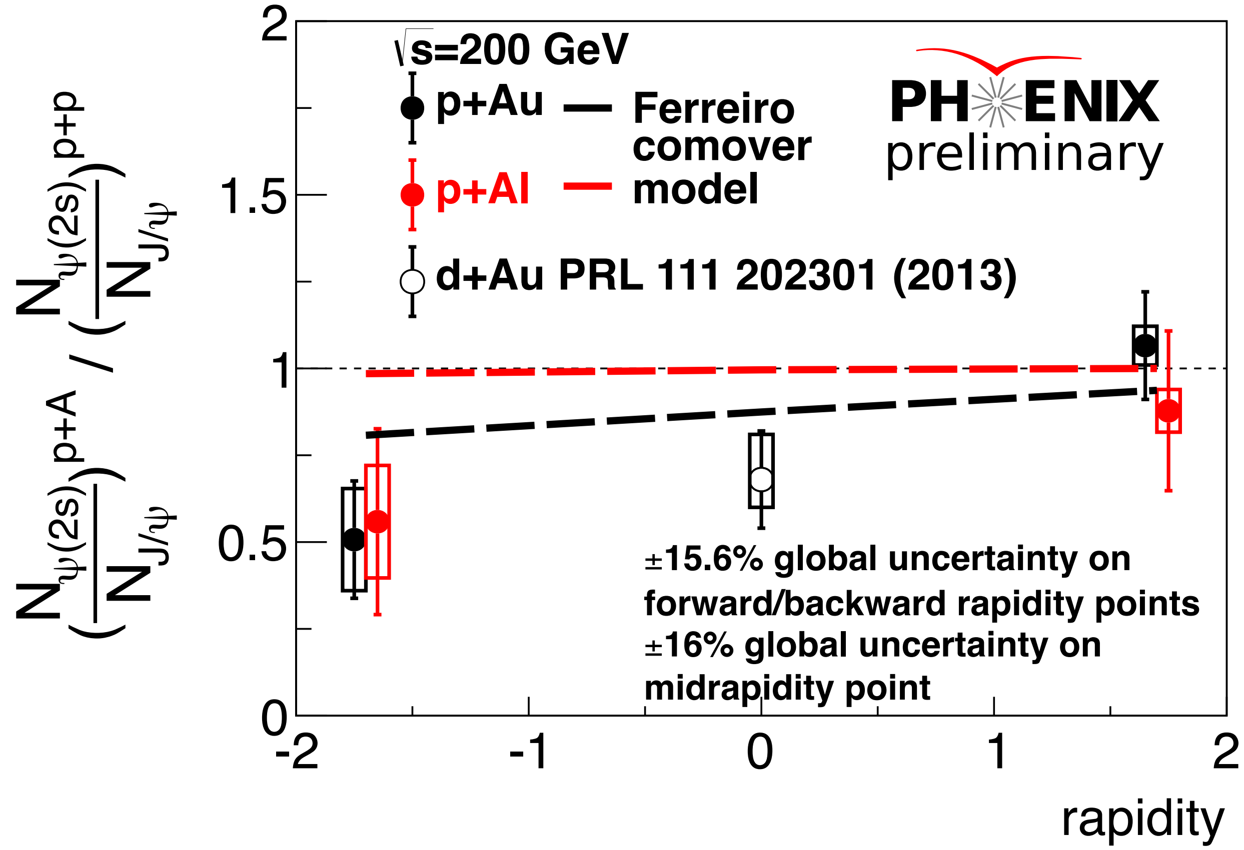
Du & Rapp arXiv:1504.00670
Hadronic gas + QGP in final state

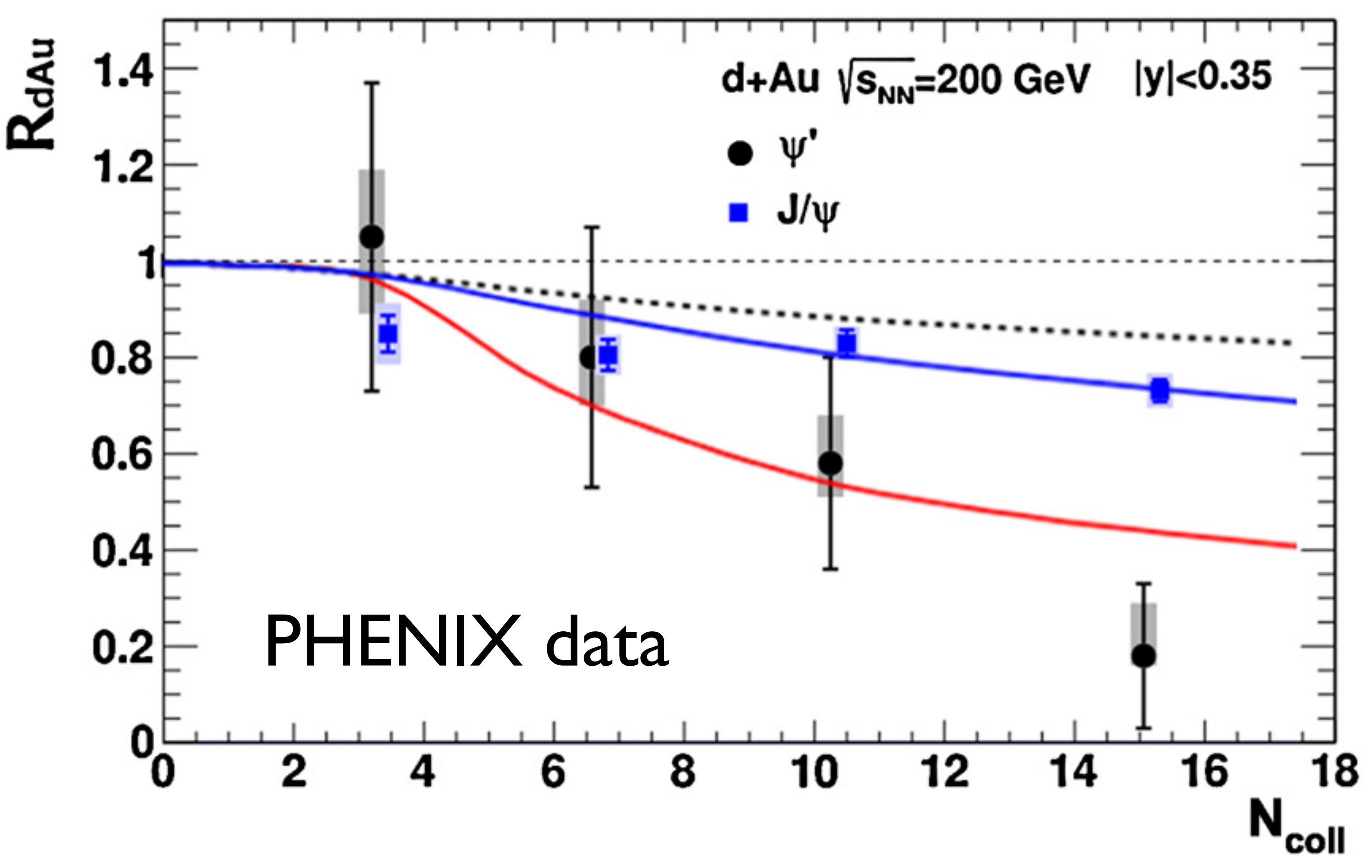


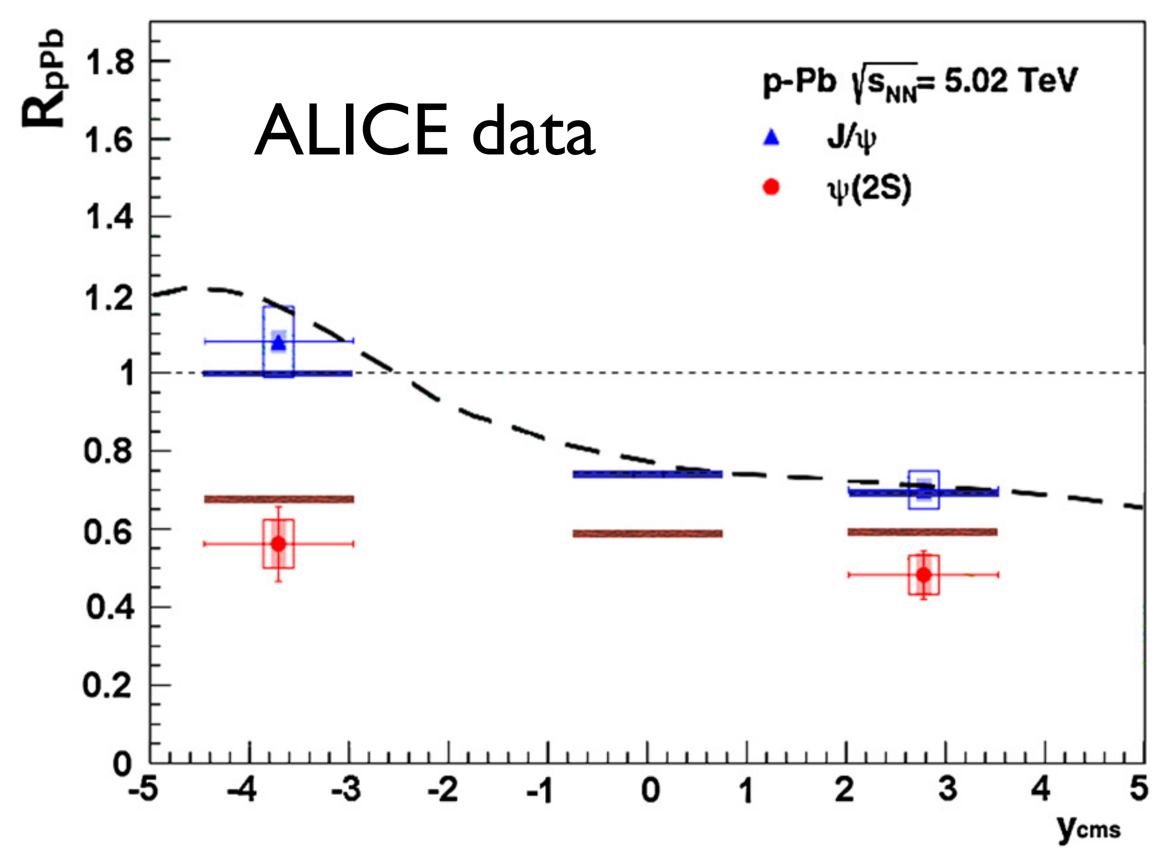
Adding ALICE data

The comover model does a reasonable job of describing available ψ(2S) and J/ψ data from both PHENIX and ALICE

But underestimates the differential suppression in both cases







Conclusions

U+U J/ψ suppression is weaker than that for Au+Au

- Consistent with dominance of coalescence over color screening

Strong indication of final state effects in p+Au ψ(2S) / ψ(1S) ratio vs rapidity

- Differential suppression of ψ(2S) - consistent with comover model

p+Au R_{pA} analysis vs centrality to come ....

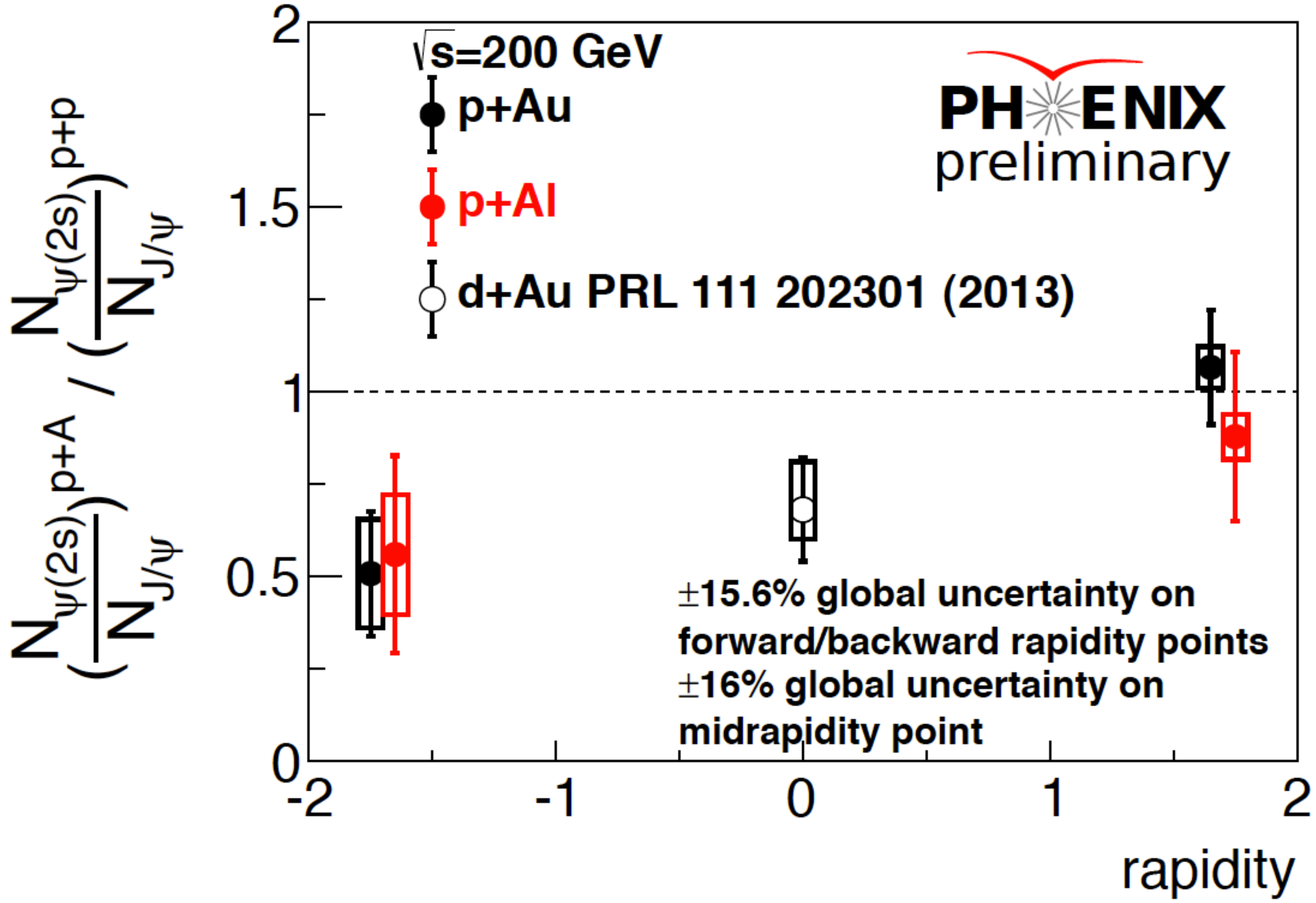
Backup

ψ’ / J/ψ ratios in p+Au and p+Al vs rapidity

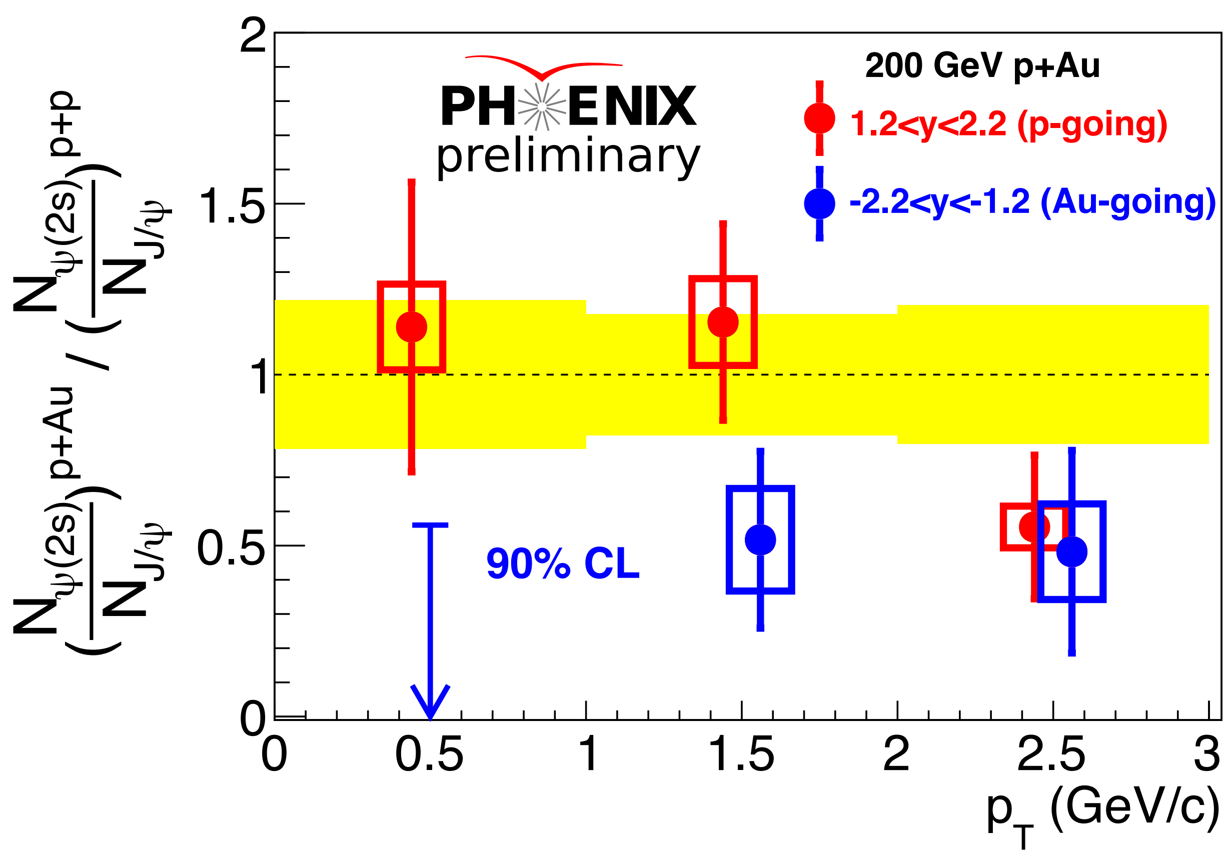
Centrality integrated ratio plotted vs rapidity for p+Au and p+Al

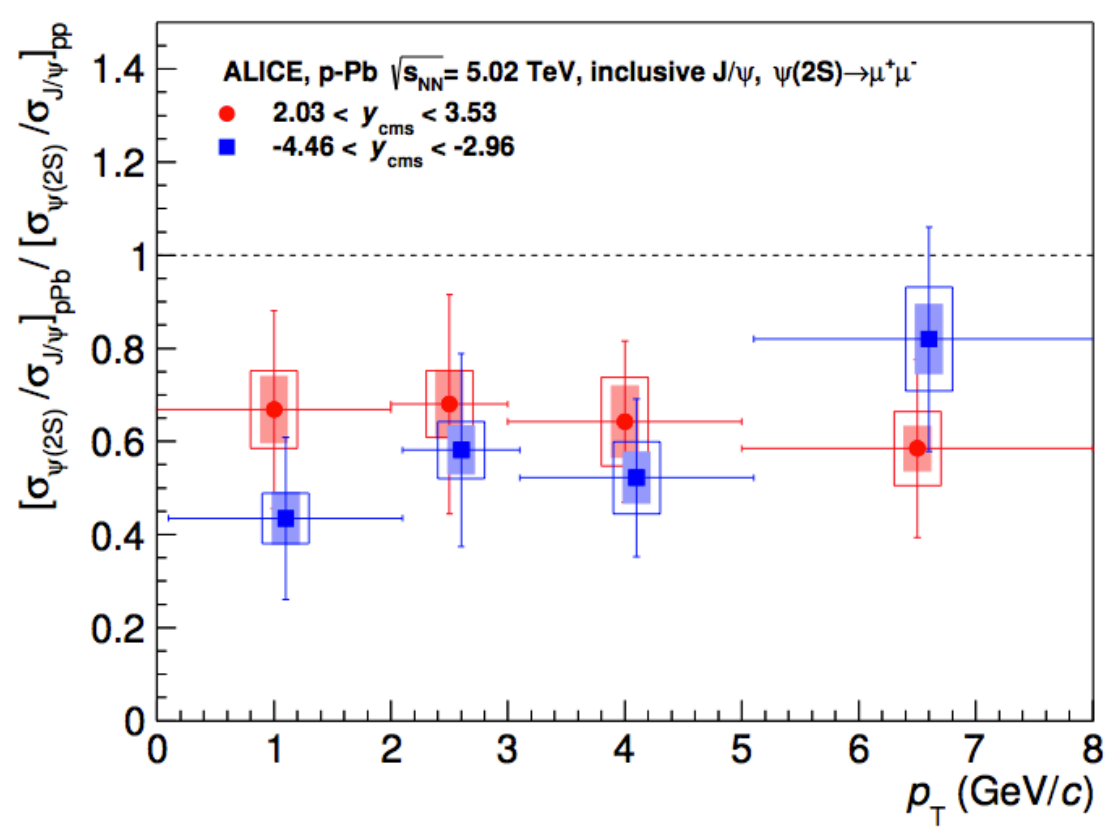
Midrapidity point is from d+Au

Strong suppression at backward rapidity
No suppression at forward rapidity



Look also at p_T dependence for p+Au:





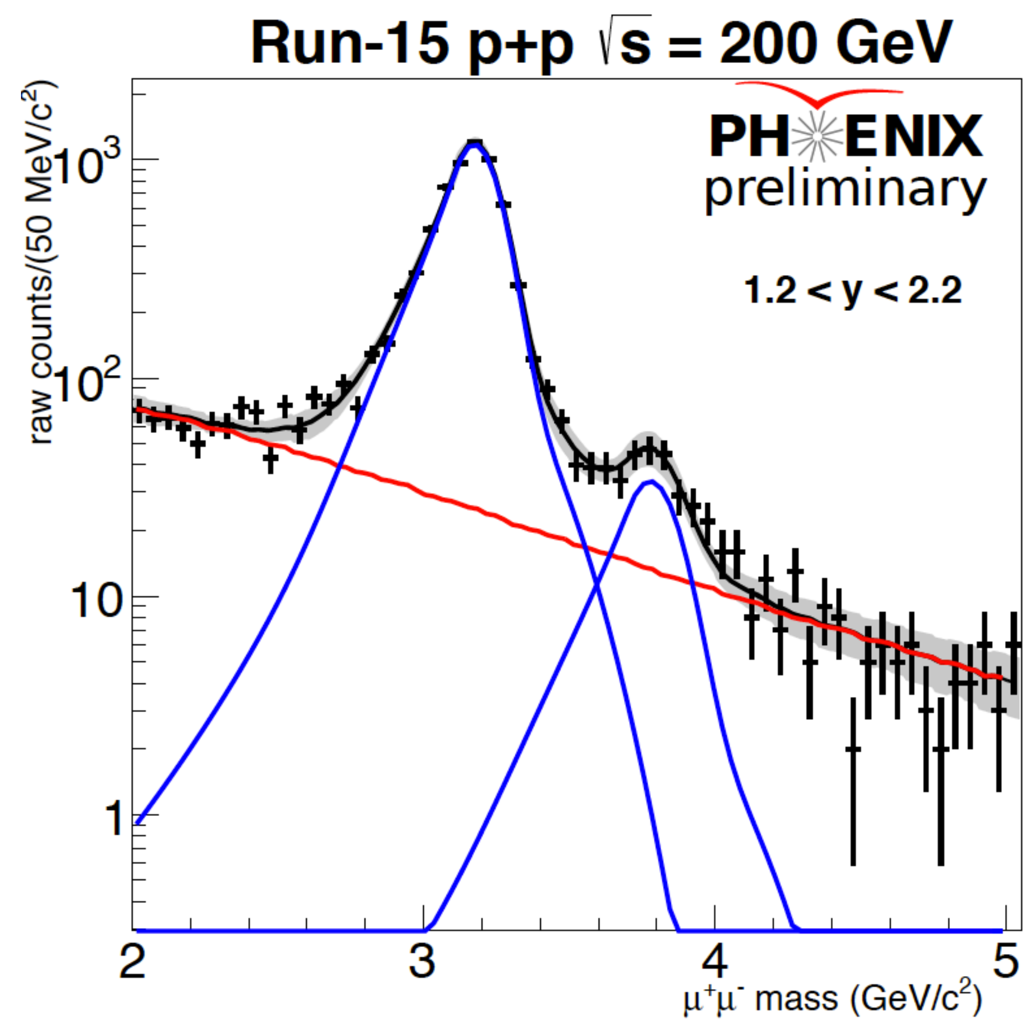
Fitting the mass spectrum for p+p, p+Au, p+Al

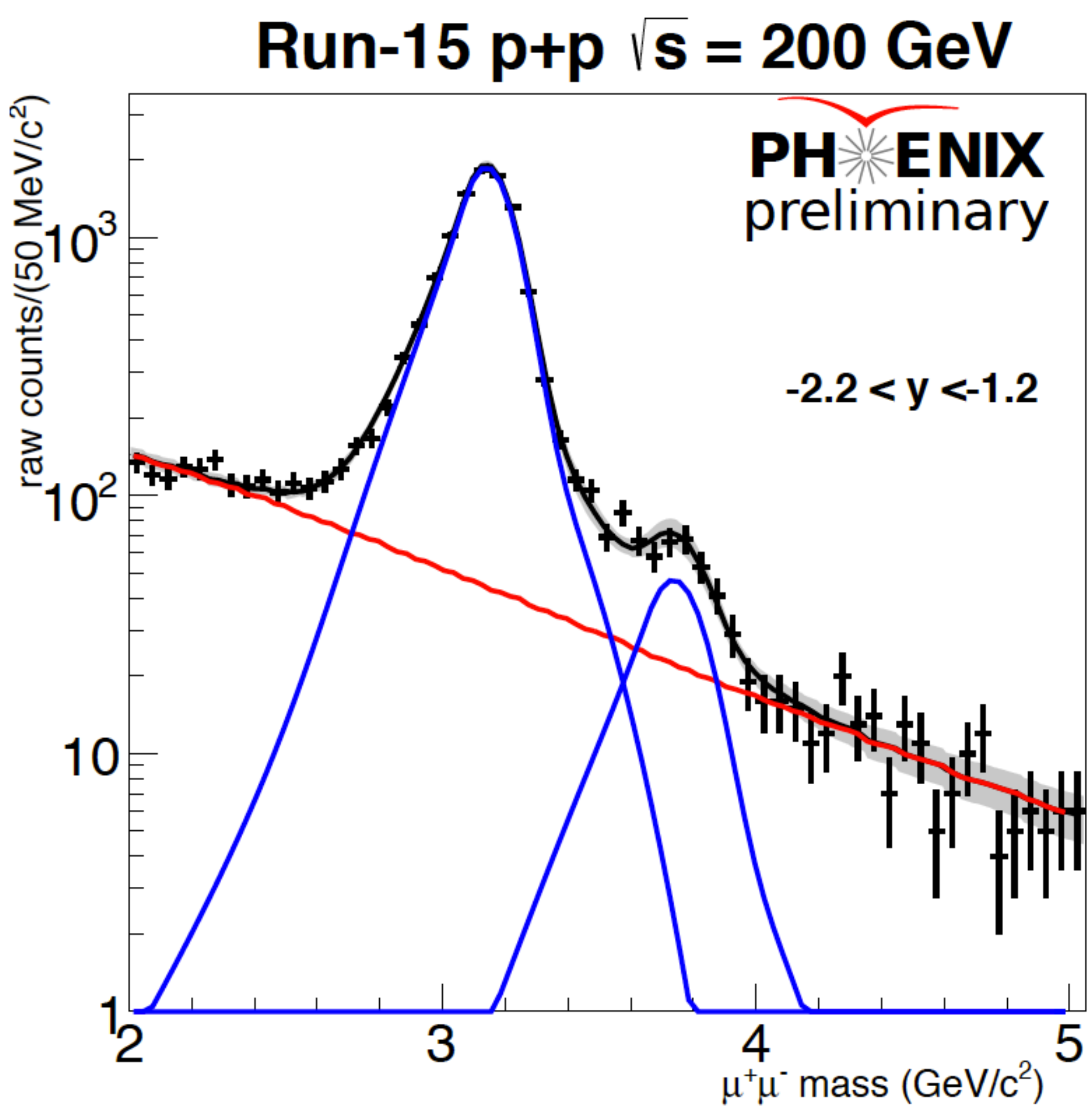
The fit is a log-likelihood fit to raw data with the following components:

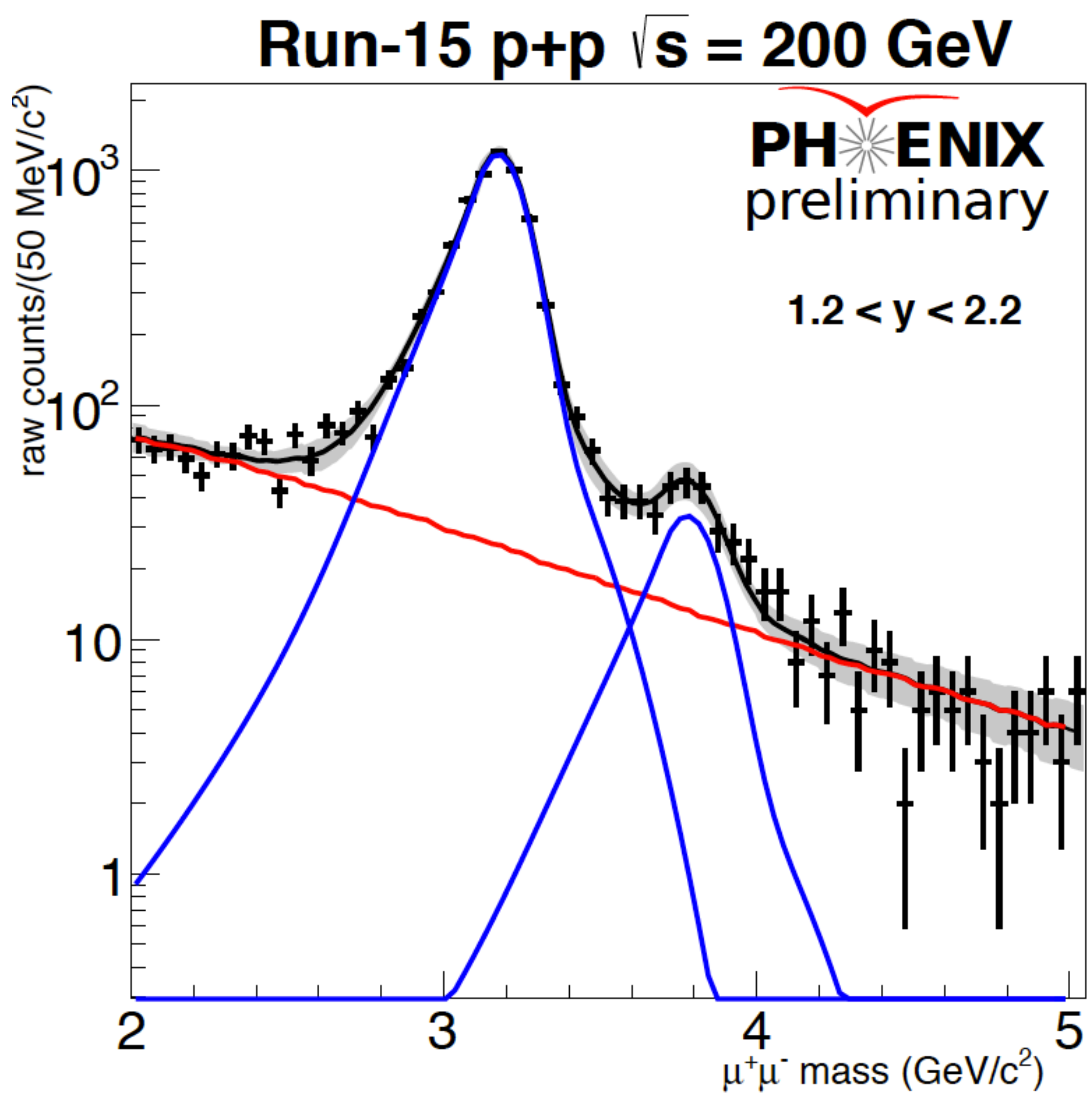
- A properly normalized mixed event combinatorial background
- An exponential function to represent correlated background dimuons
- Peaks to represent the resonances:
  - A Crystal Ball function (mass resolution + range straggling in absorber)
  - An additional Gaussian (valid pairs involving lower quality tracks)
    - Set to 200 MeV in fit, varied to determine systematic

The ψ(2S) and ψ(1S) are constrained so:

- Crystal Ball tails have the same shape, relative normalization to the peak for ψ(1S), ψ(2S)
- The ψ(2S) width is 1.15 times the ψ(1S) width
  - From sims (varied to determine systematic)
- The ψ(1S) mass floats (moves only 1-2%)
- The ψ(2S) - ψ(1S) mass difference fixed:
  - PDG x ratio of ψ(1S) mass to PDG
- Relative normalization of second gaussian is the same for ψ(2S) and ψ(1S)




Run-15 p+p √s = 200 GeV
PHENIX
preliminary
-2.2 < y <-1.2
raw counts/(50 MeV/c²)
μ+μ- mass (GeV/c²)


Run-15 p+p √s = 200 GeV
PHENIX
preliminary
1.2 < y < 2.2
raw counts/(50 MeV/c²)
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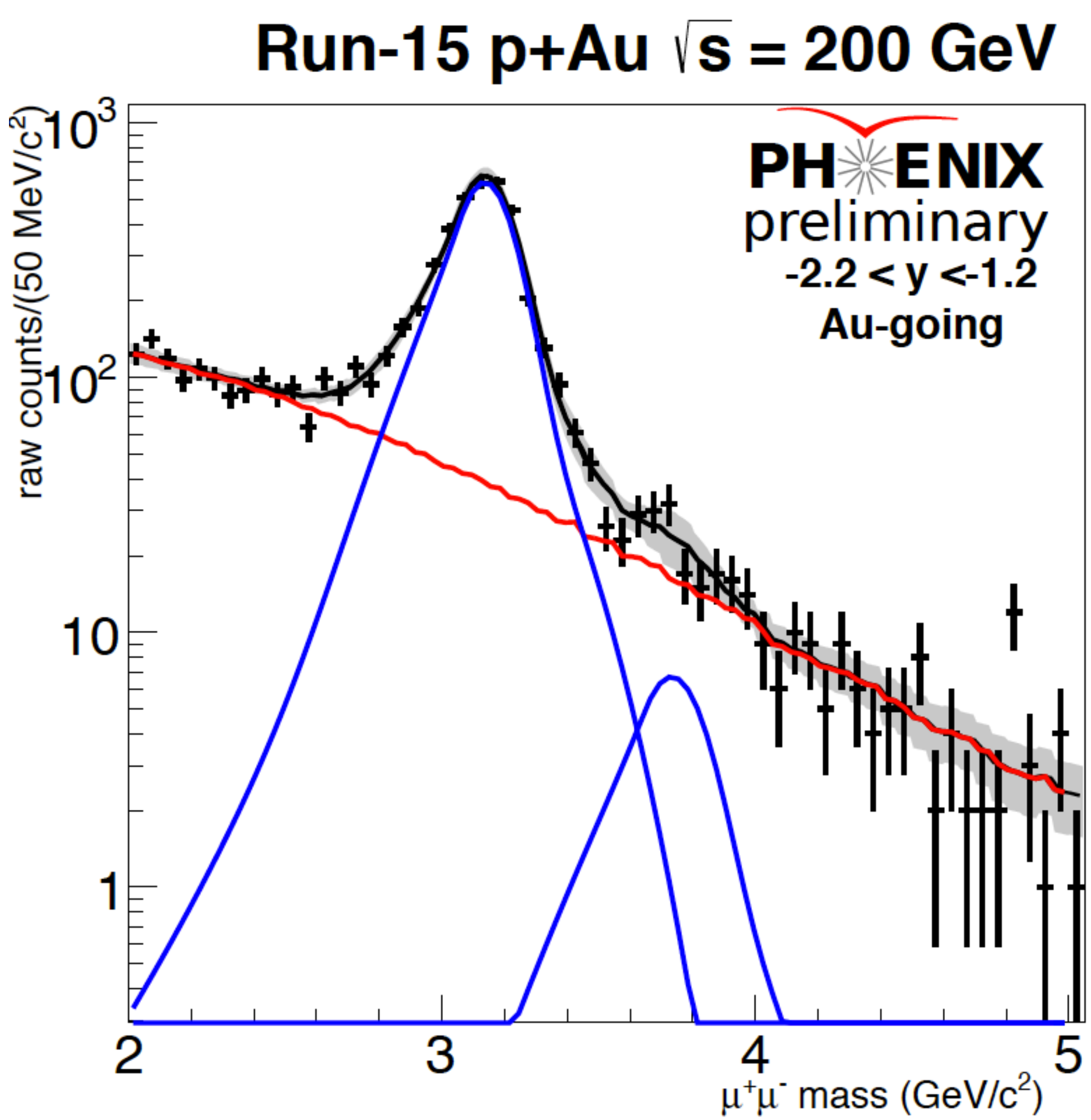
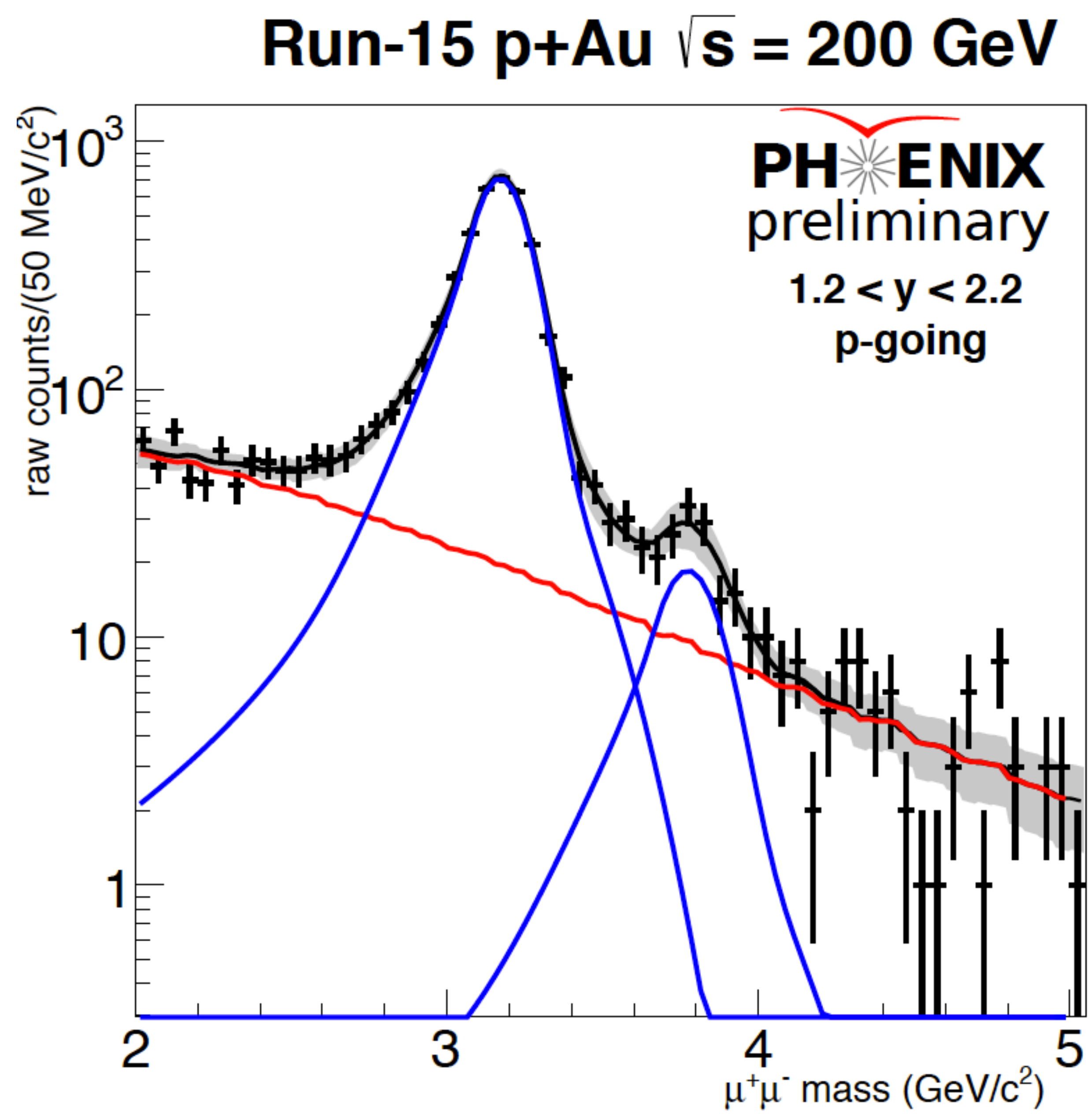


Run-15 p+Au $\sqrt{s}$ = 200 GeV
PHENIX
preliminary
-2.2 < y <-1.2
Au-going
raw counts/(50 MeV/c^2)
10^3
10^2
10
1
2
3
4
5
$\mu^+\mu^-$ mass (GeV/c^2)



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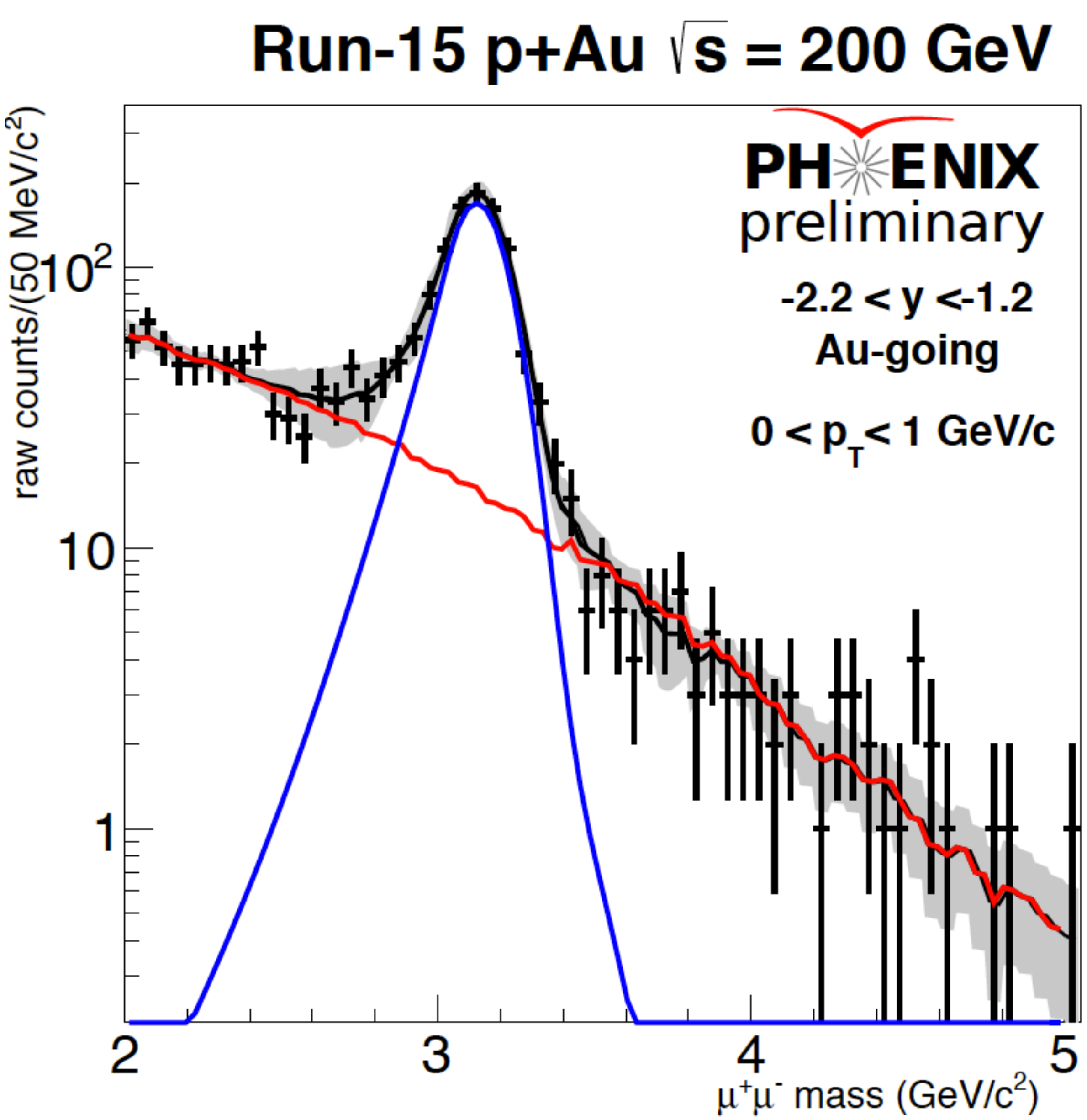
Run-15 p+Au √s = 200 GeV
PHENIX
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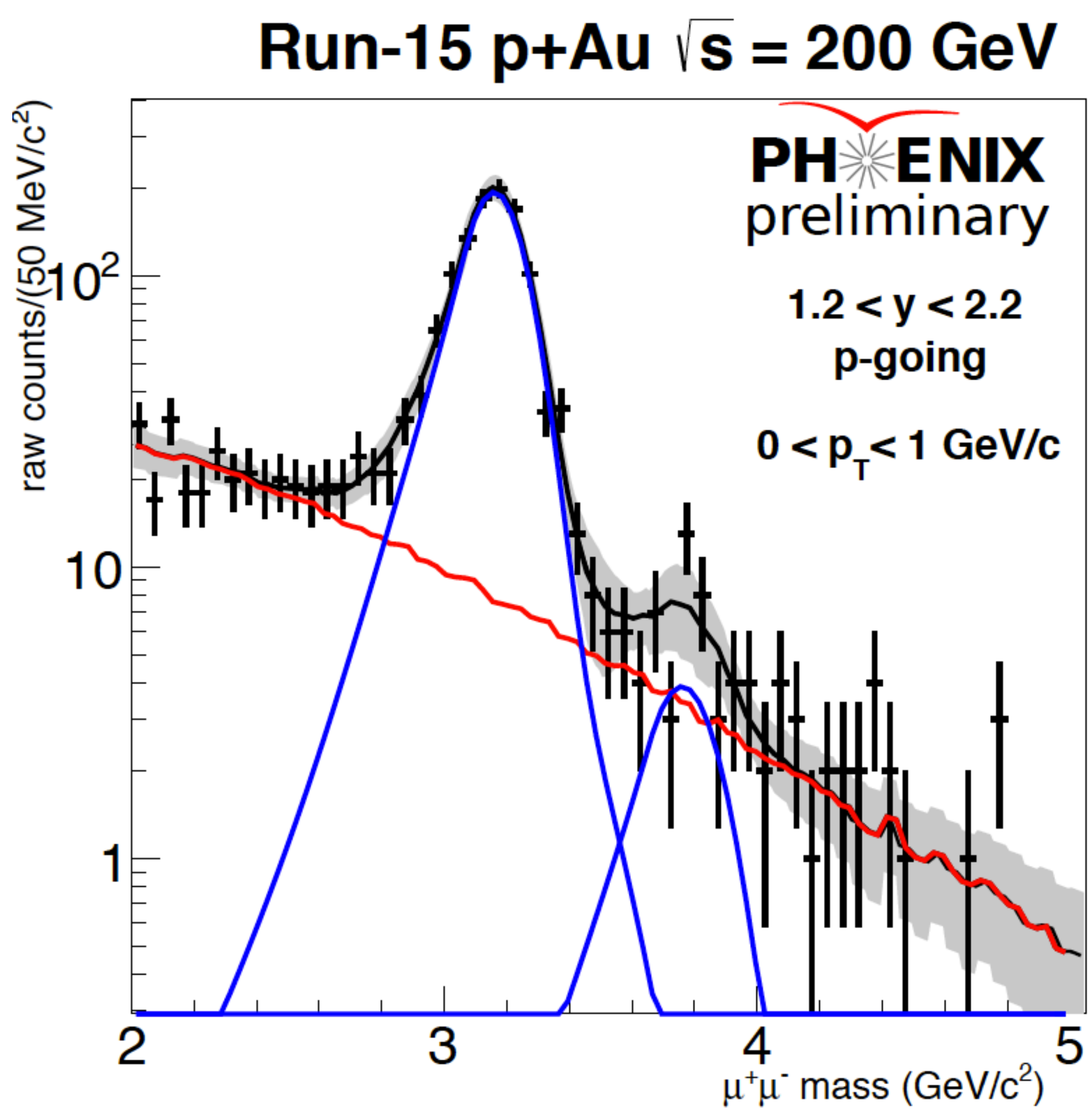
-2.2 < y <-1.2
Au-going
0 < p_T < 1 GeV/c
raw counts/(50 MeV/c²)
μ⁺μ⁻ mass (GeV/c²)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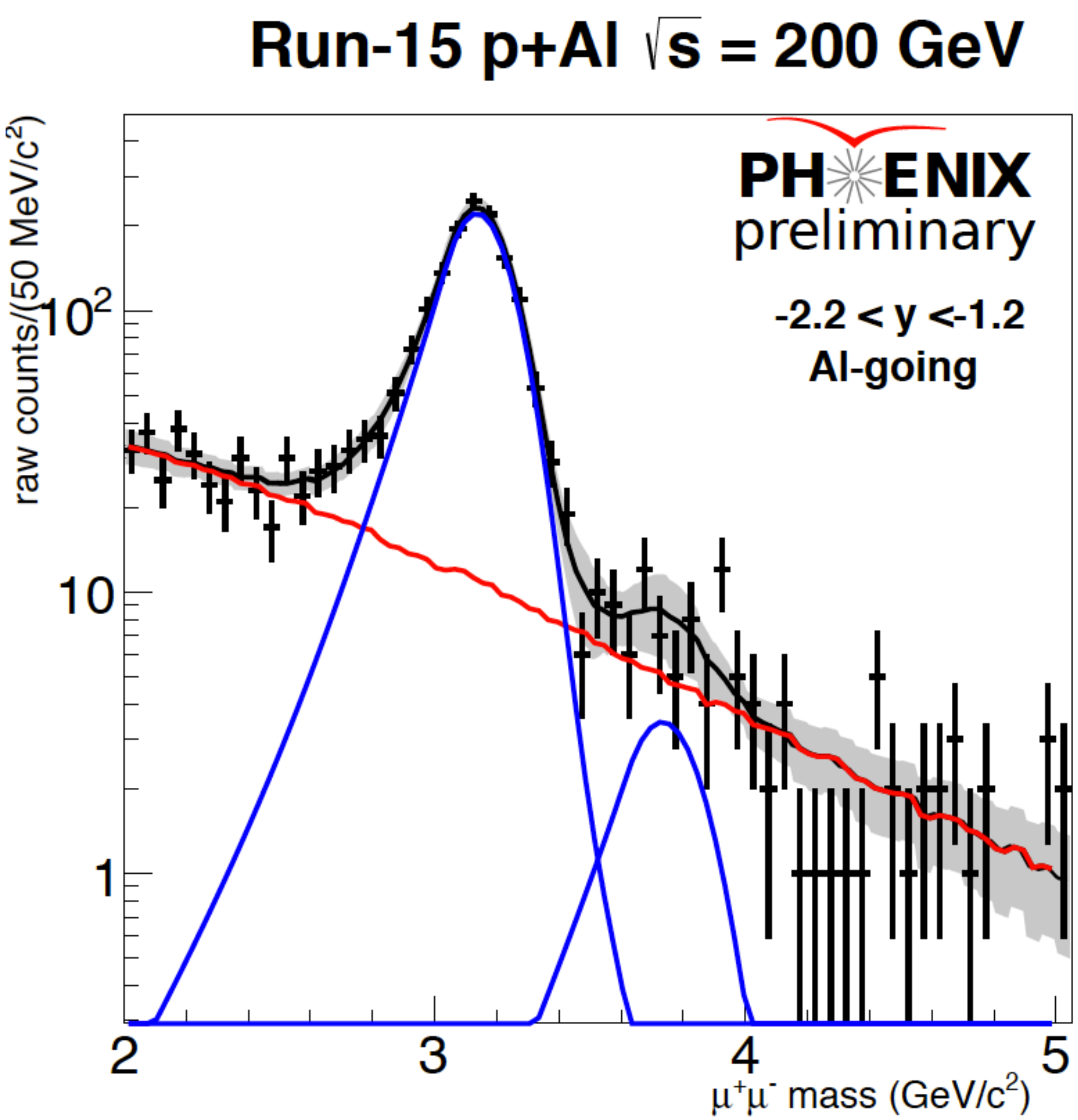
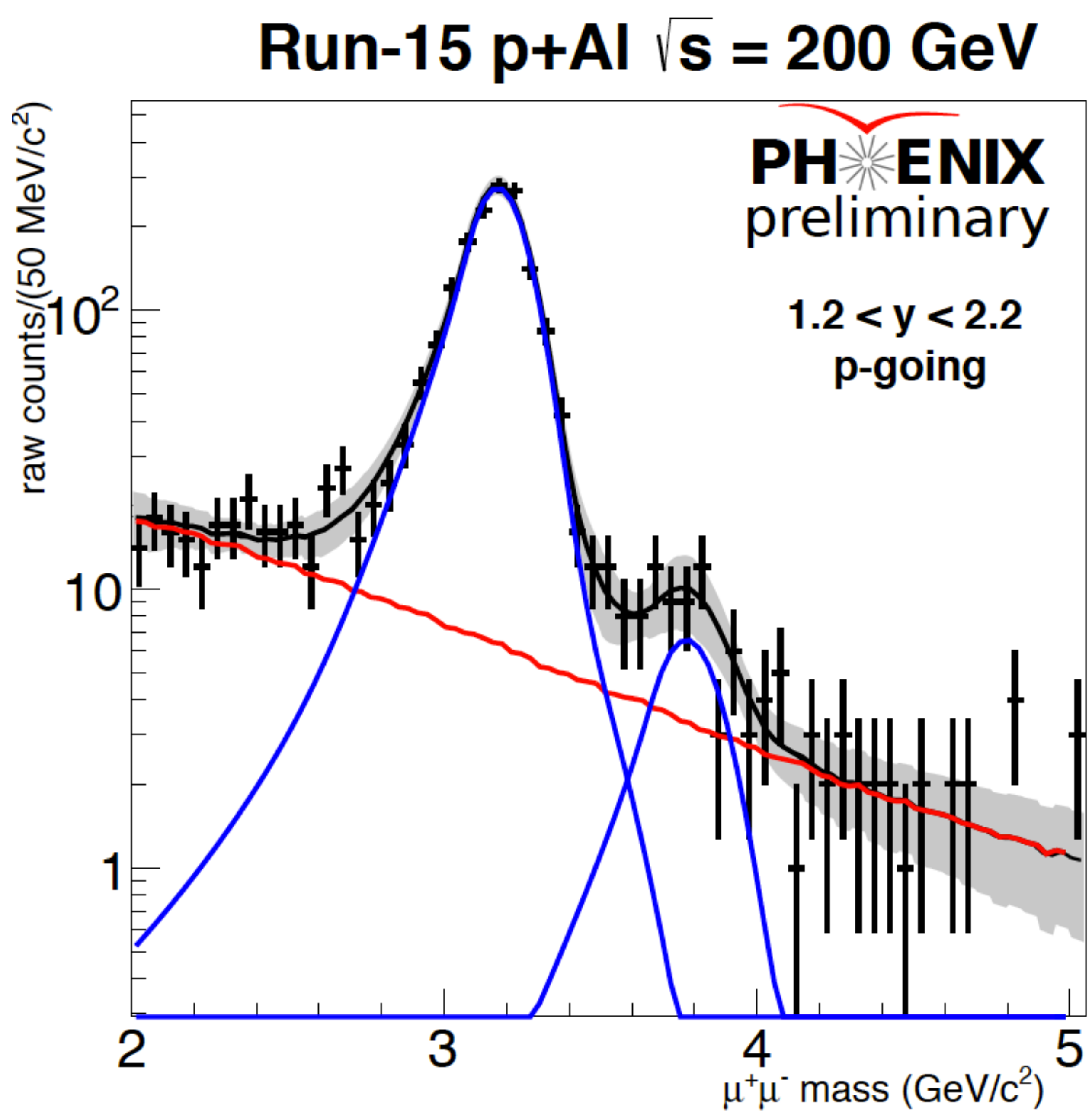

Run-15 p+Al √s = 200 GeV
raw counts/(50 MeV/c²)
PHENIX
preliminary
-2.2 < y <-1.2
Al-going
μ⁺μ⁻ mass (GeV/c²)


Run-15 p+Al √s = 200 GeV
raw counts/(50 MeV/c²)
PHENIX
preliminary
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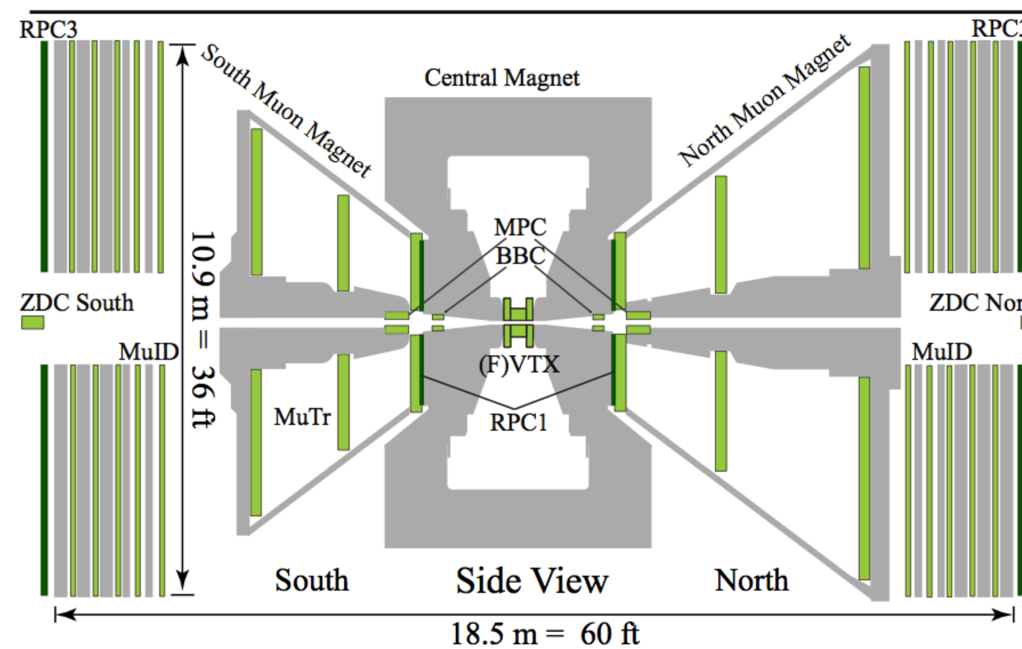
p-going
μ⁺μ⁻ mass (GeV/c²)

The PHENIX muon arms



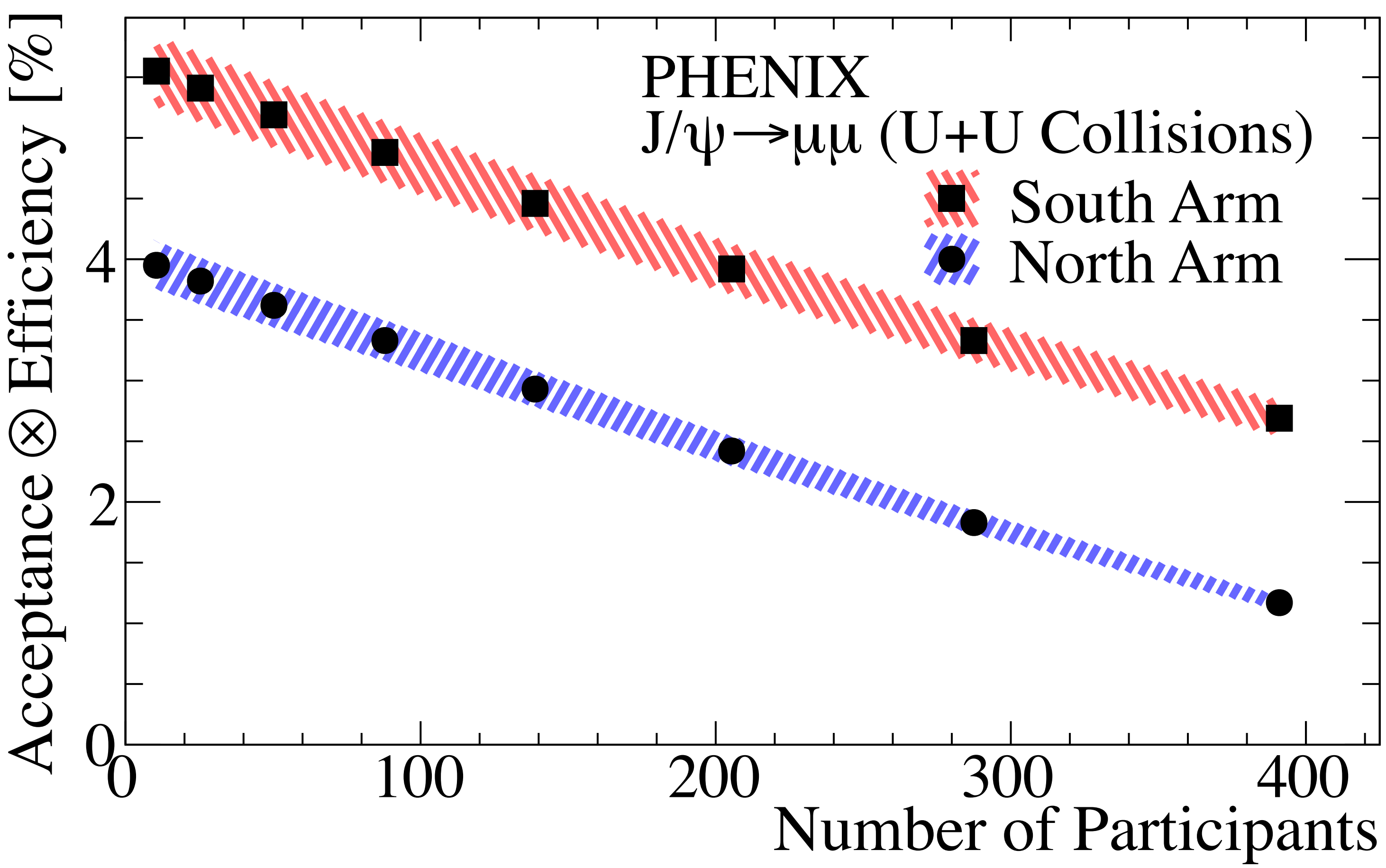
Experiment:

U+U data at $\sqrt{s_{NN}}$ = 193 GeV from RHIC 2012 run

MB trigger: 96% efficient   1.08 B events recorded

Centrality measured by BBC ($3.0 < |\eta| < 3.9$)

$J/\psi \rightarrow \mu^+\mu^-$ $1.2 < |y| < 2.2$



Acceptance⊗Efficiency:

PYTHIA $J/\psi \rightarrow \mu^+\mu^-$ events through GEANT, embedded in real data and reconstructed

Efficiency includes occupancy effects

Acceptance flat to within 30% from p_T = 0 - 8 GeV/c

U+U Signal Extraction

0-10% (most central)   60-70% (most peripheral)